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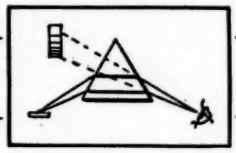

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All changes of address of members of the Optical Society of America should be communicated to the Secretary, Professor Arthur C. Hardy, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Journal of the
OPTICAL SOCIETY *of* AMERICA

VOLUME 33, NUMBER 6 JUNE, 1943

Symposium on Color-Blindness

Foreword

WHEN the OSA Board of Directors invited the Inter-Society Color Council to meet with the Optical Society in the winter of 1943, it was suggested that a symposium on color-blindness be arranged for the Optical Society by the ISCC. Since the Council had already planned to discuss this subject at its own meeting, it was an easy matter to expand these plans and arrange for a more formal and complete presentation of the subject.

A number of people were consulted in the development of this program, among them Army and Navy representatives. The concensus was that two groups of papers would be currently most useful, one to lay the background for understanding the facts of color-blindness, the methodology necessary in test preparation, a story of tests already developed, and a statement from the Armed Services regarding the reason for their need of men with normal color vision; the other to present current test developments in this country. We had hoped to include a history of work in color vision, but the time necessary to prepare such a paper was not available either to Dr. Hecht or Dr. Judd, who might in other times have done this for us.

The emphasis in this program has been upon information necessary to the understanding, use, and development of tests and test methods for discovering and diagnosing human color vision that departs from what we have come to consider "normal." In the development of the test described by Dr. Hardy in this program, cooperating Council members came more and more to the realization that material which was well known to the psychologists among them was often new to the physicists and medical men, that information widely known and used by physicists was not well known to psychologists, and that the language and knowledge of the medical man was often Greek to both the physicist and psychologist. Methodology of test preparation and presentation became increasingly important as ISCC test work went on, for it was found that a slight difference in method of presenting the test to a subject would sometimes produce unexpected and disturbing results. To the psychologist this was not news; we hope it will not be news to OSA workers after the papers of this symposium become available to them.

The first section of the program was built upon the idea of covering all the necessary factual material for practical work, relating the papers as far as possible by an exchange among the authors before publication. This exchange has been carried out, and while it will be evident that there are still certain differences in points of view expressed by the first three authors, many other points of disagreement were resolved after discussion and exchange of papers. The "pre-audit" of these papers is a contribution made by the Council through the cooperation of Dr. Judd, Dr. Dimmick, and Dr. Murray, whose papers

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constitute the first part of the symposium. These three papers appear in this number of the journal. As a part of this first section of the program it was expected that Army and Navy representatives, officially appointed to attend this meeting, would present a picture of just what they require of color vision tests. Although they were not ready to do this by the time of the meeting, they were able to take the opportunity provided by the meetings to hold many informal discussions. This opportunity, we believe, is a contribution quite as important as the formal presentations on the subject.

The second section of the symposium is devoted to a description of tests that are under current development, tests to provide information regarding various aspects of color vision defects. The committee found five such tests that had not previously been reported, and Dr. Hecht, Dr. MacAdam, Mr. Jobe, Mr. Farnsworth, and Dr. Hardy were invited to describe the one with which each was associated. These reports will appear in later issues of this journal.

DOROTHY NICKERSON
Chairman, Program Committee for March 1943 Meeting

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 33, NUMBER 6 JUNE, 1943

Facts of Color-Blindness*

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National Bureau of Standards, Washington, D. C.

1. EARLY HISTORY

COLOR-BLINDNESS is a subject requiring statistical treatment; there are types of color-blindness and a greater or lesser adherence of groups of observers to these types. These facts are disclosed in a literature which is sufficiently extensive itself to require statistical treatment. Figure 1 shows the distribution of titles according to decade for a fairly complete bibliography on color-blindness. To present some semblance of historical perspective, it is convenient to summarize the discoveries about color-blindness up to 1855 before attempting a summary of present-day knowledge.

According to this bibliography there appeared in 1684 in the *Philosophical Transactions of the Royal Society* an account by D. Tuberville of "Several Remarkable Cases in Physick Relating Chiefly to the Eyes."[51] This is perhaps the first published indication that there is such an abnormality as color-blindness. Ninety-three years later the indication is definite. J. Huddart published in the same transactions (1777) an account "Of a Person Which Could Not Distinguish Colours,"[18] and Whisson in 1778 published "An Account of a Remarkable Imperfection of Sight."[57]

However, not until Dalton's account of his own case appeared in 1798 in the *Memoirs of the Literary and Philosophical Society of Manchester*[2] could it be said that a lucid description of color-blindness had been given. Dalton said of the spectrum (p. 31), "I found that persons in general distinguish six kinds of colour in the solar image, namely, red, orange, yellow, green, blue, and purple. Newton, indeed, divides the purple in indigo and violet; but the difference between him and others is merely nominal. To me it is quite otherwise. I see only two, or at most three, distinctions. These I should call yellow and blue, or yellow, blue and purple. My yellow comprehends the red, orange, yellow, and green of others; and my blue and purple coincide with theirs." And elsewhere (p. 34), "Woolen yarn, dyed crimson, or dark blue is the same to me."

Dalton's explanation for his abnormal vision was that his eye media must absorb the red end of the spectrum strongly and so prevent him from seeing as others did. In commenting on this

* Paper presented at the Symposium on Color-Blindness at the meeting of the Optical Society of America, New York, March 5–6, 1943.

explanation, Thomas Young[61] said, ". . . it is much more simple to suppose the absence or paralysis of those fibers of the retina which are calculated to perceive red." This is the original statement of the Young theory of color-blindness, which has probably attracted more attention than any other explanation and exerts a profound influence today.

The question was immediately raised whether Dalton was really blind to the extreme red end of the spectrum and Herschel (p. 60),[58] after experimenting with Dalton as a subject told him, "It is clear to me that you, and all others so affected, perceive *as light* every ray which others do. . . . It seems to me that we (the normal-eyed) have three primary sensations where you have only two. We refer or can refer in imagination all colours to three, ... All other colours we think we perceive to be mixtures of these, and can produce them by actual mixtures of powders of the primary hues, ... Now, to eyes of your kind, it seems to me that all your tints are referable to two." However, Dalton persisted in his own explanation, and was not proven to be wrong until after his death in 1844 when posthumous examination of his eye media showed them to be normally transparent for red light (p. 54).[58]

Color-blindness aroused much interest during the early part of the nineteenth century, and was called Daltonism by European writers of those times over the protests of British scientists, who thought Dalton should be known as the originator of the atomic theory of matter rather than the arch-type of a defect of vision. A continuing controversy raged concerning whether color-blind observers are really blind to red. The answer was given by Seebeck[48] in 1837 that some color-blinds are relatively insensitive to red, but most are not.

In 1852 Helmholtz[13] gave an account of compound colors on the basis of the Young theory, and in 1855 Maxwell[31] pointed out that according to this theory it is possible to define the confusion colors of color-blinds in terms of the color triangle now known as the Maxwell triangle. He said, "If we find two combinations of colours which appear identical to a color-blind person, and mark their positions on the triangle of colours, then the straight line passing through these points will pass through all points corresponding to other colours, which, to such a person, appear identical with the first two."

Thus, within 60 years of Dalton's description of color-blindness many of the chief questions had been raised and answered correctly. Color-blindness was found to have a number of forms, chief of which correspond to a reduction from the normal three-component visual system to a two-component system as in Dalton's case of partial color-blindness, or to a one-component system as in cases of total color-blindness. The chief characteristic of color-blindness, that of chromaticity confusion, was recognized and Maxwell had pointed out how these confusions could be represented accurately on the Maxwell triangle. Furthermore, Dalton had correctly analyzed his own sensations as yellow and blue. It was known that there are degrees of chromaticity confusion as well as different kinds. Permanent or inherited color-blindness was found in some degree or other in about 10 percent of the male population, and in a considerably smaller fraction of the female population. Cases of color-blindness associated with injury and disease had also been established.

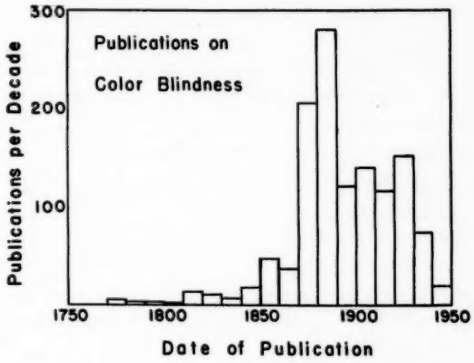

FIG. 1. Distribution of 1200 publications on color-blindness by decade. Note the great activity between 1870 and 1890, and the continuing steady interest since that time.

Thus in 1855 it would have been possible for a clairvoyant to make an outline of the chief facts of color-blindness from the then existing literature. But there was considerable contradictory evidence and many conclusions drawn from faulty or insufficient ground. Thus, because of lack of photometric equipment, Herschel failed

to establish that Dalton was less than normally sensitive to the long-wave end of the spectrum in spite of the fact that both Young's explanation and Dalton's own explanation required it. It had been correctly pointed out that, in spite of a proven connection between color vision and the pigmentation of the eye media, the color of eyes and hair is no reliable guide to color-blindness; but the question was still open whether color-blind observers could be detected by a flatness of the skull just beneath the eyebrows. One eminent British authority prescribed test methods foreshadowing the Holmgren wool test, but also suggested (p. 152)[58] that the detection of color-blind observers might also be assisted by "a singular expression of their eyes, either a startled expression as if they were alarmed" or "an aimless eager glance, as if seeking to perceive something but unable to find it." This point was raised again in 1881.[19] Almost the first theory of color-blindness, the Young theory, still commands respect, but there were other theories to choose from, the eye-pigment theory, the choroid-coat coloration theory, and various phrenological theories, none at all elaborated so as to be amenable to check. Thus we may say that in 1855 the important questions about color-blindness had been raised and qualitatively correct answers had been supplied, but the qualitative facts had not been proven, they had merely been suggested; and of the quantitative facts almost none had been established.

The year 1855 is a convenient one for taking stock not only because the ground-work had been laid by Helmholtz and Maxwell for the evaluation of the precise properties of color-blind vision, but also because the importance of excluding color-blind observers from certain occupations was beginning to be generally recognized. The bibliography lists about 100 titles up to 1855 or less than 10 percent of the total of 1200 titles; see Fig. 1. The period of greatest activity in the study of color-blindness was between 1870 and 1890 and the interest has continued steadily up to the present time. From this extensive literature, the facts of color-blindness have been drawn. It is the purpose of this paper to present a summary of these facts, and it is hoped that they will be given essentially their proper emphasis and perspective in spite of the fact that only 80 of the 1200 publications have been studied in any detail. This summary has four parts, (a) classification of visual systems, (b) causes of color-blindness, (c) luminosity functions of red-green-blind and red-green-weak observers, and (d) chromaticity confusions of red-green-blind observers.

2. CLASSIFICATION OF VISUAL SYSTEMS

Seebeck's classification of vision into normal and two types of abnormal vision has been corroborated by scores of studies since 1837. In addition to these three classes many more have been established. Table I summarizes the characteristics of the chief classes of vision which are now fairly well established as well as several which are still subjects of controversy.

Normal vision, and indeed any type of visual system, may be conveniently summarized by giving a description of an equal-energy spectrum as it appears to an observer of that type. The equal-energy spectrum is one having constant radiance per unit wave-length. Every stimulus affecting the eye is either a portion of this spectrum or may be regarded as a combination of a number of such portions. We may therefore sketch approximately the properties of an observer by giving his description of the spectrum just as Dalton did for his own vision.

A. Normal Vision

To the normal observer the spectrum appears as a series of chromatic colors varying from dim red through orange, yellow, brilliant yellow-green, green, blue, to dim violet. The brightest part of the equal-energy spectrum under usual observing conditions is between wave-lengths 540 and 570 millimicrons (yellowish green), and from this point (average 555 mμ) toward both greater and smaller wave-lengths the brightness progressively diminishes. These facts are represented by the luminosity function of the average eye whose maximum is at 555 mμ. The colors seen by a normal observer can be duplicated with trivial exceptions by mixtures of three lights, a red light, a green light, and a blue light, each light being independently adjustable in amount; two lights are insufficient and more than three not necessary. On this account normal vision is classed as trichromatic. A corollary of trichro-

TABLE I. Classification and characteristics of the various visual systems.

Designation of type according to number of components	Discriminations possible by this type	Wave-length of the maximum of luminosity function, mμ	Wave-length of neutral points in spectrum, mμ	Non-theoretical designation (v. Kries)[1]	Theoretical designations		
					Young-Helmholtz	Hering	G. E. Müller
Trichromatism	Light-dark Yellow-blue Red-green	555	None	Normal system	Normal system	Normal system	Normal system
	Light-dark Yellow-blue Red-green (weak)	540	None	Protanomaly[2]	Abnormal red function	——	Alteration[5] system
	Light-dark Yellow-blue Red-green (weak)	560	None	Deuteranomaly[2]	Abnormal green function	Red-green weakness	Alteration[5] system
	Light-dark Red-green Yellow-blue (weak)	560	None	Tritanomaly[3]	Abnormal violet function	Yellow-blue weakness	Alteration[5] system
Dichromatism	Light-dark Yellow-blue	540	493	Protanopia[7]	Red blindness	——	Outer red-green blindness
	Light-dark Yellow-blue	560	497	Deuteranopia[7]	Green blindness	Red-green blindness	Inner red-green blindness
	Light-dark Red-green	560	572	Tritanopia	Violet blindness	——	Outer yellow-blue blindness
	Light-dark Red-green	560	470 580	Tetartanopia[4]	——	Yellow-blue blindness	Inner yellow-blue blindness
Monochromatism	Light-dark	510	All	Congenital total color-blindness[8]	——	——	Cone blindness[6]
	Light-dark	560	All	Acquired total color-blindness[8]	——	Total color-blindness	Inner total color-blindness, Type I
	Light-dark	540	All	——	——	——	Inner total color-blindness, Type II

[1] See literature reference 28, p. 402.
[2] König (reference 25) proposed the designation, anomalous trichromatism, for the classes later designated separately by Nagel (reference 37) in an extension of the v. Kries terminology.
[3] This extension of the v. Kries terminology was proposed by Engelking (reference 4).
[4] This extension of the v. Kries terminology was proposed by Müller (reference 34, p. 68).
[5] The term, alteration system, was proposed originally by v. Kries (references 27, 28, p. 408); Müller also uses Nagel's terminology; see note 2.
[6] The term, cone blindness, is based upon the duplicity theory of v. Kries and Parinaud, now widely accepted (reference 33).
[7] Protanopic observers are sometimes called scoterythrous (reference 47), and deuteranopic, photerythrous.
[8] Total color-blindness is often called achromatopsia (reference 49) or achromatopia.

matism is that three kinds of discrimination are possible. It is convenient to classify the discriminations of a normal observer as light-dark, yellow-blue, and red-green; that is, a normal observer can tell light colors from dark ones, yellowish colors from blue ones, and greenish colors from red ones. For example, he can tell greenish grays from reddish grays, greenish yellows from reddish yellows, and greenish blues from reddish blues; these are all examples of red-green discriminations.

The types of abnormal vision may be classed under anomalous trichromatism, dichromatism, and monochromatism.

B. Anomalous Trichromatism

An observer possessing anomalous trichromatic vision requires a mixture of three lights to produce all the colors which he is capable of experiencing just as a normal trichromat does, but to produce a given color he requires proportions significantly different from those required by the normal observer. If he is only mildly anomalous, his description of the equal-energy spectrum will agree somewhat with the normal; but if he is extremely anomalous, it will scarcely differ from that of a dichromat. The distinctions made by such an observer are light-dark, yellow-blue, and red-green; but the ability to make one of the chromatic distinctions (usually red-green) is relatively weak. There are two fairly prevalent types of anomalous trichromat, called protanomaly and deuteranomaly, and a rare type, tritanomaly, recently discovered by Engelking.[4] Observers of these types are intermediate in ability to make chromatic distinctions between

normal observers and dichromatic observers of the protanopic, deuteranopic and tritanopic types respectively, to be discussed presently. Thus, the anomalous observer can make with difficulty the distinctions which the corresponding dichromat cannot make at all. However, in other respects anomalous trichromatism is not intermediate between normal trichromatism and dichromatism. For example, the luminosity function of protanomalous observers of all degrees is deficient at the long-wave end like that of the protanope. This deficiency is indicated roughly in Table I by the average wave-length (540 mμ) of the brightest part of the equal-energy spectrum. The deuteranomalous and tritanomalous observers on the other hand have luminosity functions well within normal limits.

C. Dichromatism

An observer possessing a dichromatic visual system requires a mixture of but two lights to produce all the colors which he is capable of experiencing. He can make two kinds of visual discrimination, one achromatic (light-dark) and one chromatic (either yellow-blue or red-green, usually the former).

The spectrum to an observer having red-green blindness appears in two hues only; the short-wave end of the spectrum appears blue; the long-wave end, yellow (just as Dalton described it in 1798). These two bands are separated by a region at about 495 mμ, which like average daylight has no hue at all, called the neutral point. From zero at the neutral point the saturations of the spectrum colors increase toward both the long-wave and the short-wave ends. There are two subtypes of red-green blindness; one characterized by abnormally low luminosity of the long-wave portion of the spectrum, the other by a substantially normal luminosity function.

The first subtype is that possessed by Dalton and called by Helmholtz (p. 360)[14] *red-blindness* following Young's explanation. The nontheoretical designation of this type, protanopia, proposed by v. Kries,[27] is probably the most widely used.* This designation is an improvement over the theoretical designation, red-blindness, because such a term taken from Young's original hypothesis suggests that protanopes see nothing but green and violet, whereas cases of monocular protanopia have shown that they really see yellow and blue.[3] Adherents of the Müller theory of vision also use the designation "outer (or retinal) red-green blindness" because the Müller theory,[34] places in the retina the defect causing this abnormality of vision. The Hering theory does not account for it. An alternate descriptive term, scoterythrous,[47] is sometimes substituted for protanopic. In Table I the shortening of the long-wave end of the spectrum for protanopes is indicated by the average wave-length (540 mμ) of the maximum of the protanopic luminosity function. This wave-length is definitely, though only slightly, beyond the normal limits.

The second subtype of dichromatic vision is known as deuteranopia, formerly called green blindness by Helmholtz following Young's explanation. The Müller theorists call this abnormality of vision "inner, or neural, red-green blindness" because they place in the optic nerve the structural defect causing it. The luminosity functions of deuteranopes fall well within normal

* By derivation the terms, protanopia and deuteranopia, are rather closely allied to the theoretical terms, red-blind and green-blind, which they were intended to replace. That v. Kries wished them to refer only to experimental facts is indicated by the following discussion (reference 28, p. 402) written by him in 1911:

"The connection thus established and experimentally verified between the two types of dichromats and between both of them and normal trichromats is identical with what Helmholtz had already supposed to be probably the case. In order to have a name for it that expresses simply the experimental results without involving any theoretical consequences, the writer speaks of the two colour systems of dichromats as being *reduction forms* of normal vision. At any rate the simplest and most natural explanation of these abnormalities is to regard them as being *deficiency effects*, in the sense that each of these types lacks one of the component factors of the visual organ as assumed in the Helmholtz theory. This was just the idea that was conveyed by the terms red-blind and green-blind that were formerly in use. And yet these expressions have been the source of much misunderstanding, for which the words themselves are perhaps partly responsible. As a matter of fact, green-blind persons are not really blind to green light, nor red-blind persons to red light; nor can it be assumed that the former lack the sensation of green and the latter the sensation of red. (Moreover, simply because the dichromat is supposed not to have some one of the three components of the organ of vision, we have no right at all to infer that ordinary heterogeneous daylight which has no colour for a normal eye looks blue-green to one kind of dichromat and purple to the other kind.) In order to have brief descriptive terms for the relation that has been found to exist here, without expressing any theoretical bias, the writer suggests the names *protanopes* and *deuteranopes* to describe the two kinds of dichromats, that is, persons who lack the first component or the second component, respectively, of the normal visual organ."

limits, but there is some indication that on the average they are higher than normal on the long-wave side; compare, in Table I, the maximum of the normal luminosity function (555 mμ) with that for deuteranopes (560 mμ). Deuteranopic observers are also sometimes known as photerythrous.[47]

Dichromatic vision may also take the form of yellow-blue blindness which is a rare form associated chiefly with diseases of the eye. Objects appear to such an observer a good deal as they do by candlelight to a normal observer. The spectrum to an observer having yellow-blue blindness appears in but two hues, red and green; his luminosity function is normal or nearly so, a possible slight defect on the short-wave end being hard to separate from the effects of yellow pigmentation of the eye media, which is very common. There are two subtypes of yellow-blue blindness.

The first subtype is called tritanopia. A tritanopic observer sees one neutral point in the spectrum (at about 570 mμ) which divides it into a red (long-wave) and a bluish green (short-wave) portion. The Young-Helmholtz theory gives it the name of violet blindness. The Müller theory calls it "outer yellow-blue blindness" as well as tritanopia, in analogy to protanopia or outer red-green blindness. The Hering theory does not account for it.

The second subtype is called tetartanopia by Müller who also refers to it as "inner yellow-blue blindness" and makes it analogous to deuteranopia or inner red-green blindness. Tetartanopia is characterized by two neutral points in the spectrum, one at about 580 mμ, the other at about 470 mμ. To a tetartanope the spectrum appears red from the long-wave end down to the first neutral point, green between the neutral points and red again at the short-wave end. This type is so rare that many classifications fail to include it. Only 5 cases have been studied and reported. It is associated with impaired ability to distinguish red from green and therefore resembles to a considerable extent total color-blindness.[49]

D. Monochromatism

An observer possessing this type of abnormality requires but a single light to produce all the colors which he is capable of experiencing; he can match any two stimuli merely by adjusting them to equal brightness; he is capable of light-dark discrimination, but of no chromatic discrimination whatsoever. His spectrum does not have merely one or two neutral points; it is all neutral. On this account monochromatism is rather aptly called achromatopsia or achromatopia.[49]

The most common form of monochromatism is often called cone blindness since it is universally ascribed to non-functioning of the retinal cones; the most common designation is congenital total color-blindness. Not only do monochromats of this type have at all times at least a trace of the central scotoma characteristic of normal twilight vision, but they also tend to have photophobia, or fear of light, which is characteristic of owls and of the normal dark-adapted observer, and which is ascribed to rod vision. Further common characteristics of such observers are low visual acuity and nystagmus or side-to-side eye-movements as if in an attempt to improve deficient visual acuity by using retinal areas now to the one side, now to the other side of a central blind area. The luminosity function of a cone-blind observer is the same as that of a normal dark-adapted observer; compared to the normal luminosity function it is greatly deficient on the long-wave side, and has a maximum at 510 instead of 555 mμ.

There are two less common forms of monochromatism both of which are thought to arise solely from disease of the eye and the optic nerve. Unlike cone blindness these forms are characterized by normal visual acuity as well as good foveal vision. The first type is characterized by a normal or deuteranopic luminosity function with maximum at about 555 mμ or 560 mμ; the second by a protanopic luminosity function whose maximum is at about 540 mμ. The second form is regarded as the result of an observer being born with protanopic vision and then acquiring tritanopia as a result of disease. Both are known as acquired total color-blindness.

3. CAUSES OF COLOR-BLINDNESS*

A. Congenital Color-Blindness

All forms of visual system except the two atypical forms of monochromatism just discussed

* Prepared in collaboration with Dr. LeGrand H. Hardy.

may be inherited; the abnormal forms may therefore be considered as congenital defects. Protanopia, protanomaly, deuteranopia, and deuteranomaly are regarded as sex-linked characteristics.[43, 55, 59] According to this view, a mother with normal color sense may transmit any of these defects to her sons, but her daughters by a normal father are either normal or become themselves transmitters of the defect. Color-blind daughters result either from the union of a color-blind man with a woman who is a transmitter of the same type of defect, or from parents both of whom have the same defect. By this view congenital color-blindness should be much more prevalent among males than among females. Table II, based chiefly upon the study of 5000 school children by v. Planta[43] and 18,000 school children by Waaler,[55] shows how closely the statistical facts agree with this view. Eight percent of the boys were found to possess a color defect, while less than one-half of one percent of the girls were color-blind. It is obvious, however, that by this view at least 8 percent of women must be transmitters of color-blindness.[55]

Total color-blindness is only slightly more prevalent among males than females. Estimates of the frequency of occurrence of total color-blindness have also been included in Table II, and are based upon Köllner's[24] summary of studies by Göthlin[8] and Peter.[40] Total color-blindness is regarded as a simple recessive characteristic; total color-blinds are frequently found to have parents having close blood relationships.

The estimates of one ten-thousandths of one percent for the occurrence of tritanomaly and tetartanopia correspond to three cases of tritanomaly,[4, 5, 11] and five cases of tetartanopia reported in the literature.[1, 15, 16, 34, 45, 46, 52, 53] All three cases of tritanomaly were closely related males; so there is some evidence that this defect is also sex-linked. Congenital tritanopia is but rarely studied and reported. Perhaps such cases are less seldom detected because the practically important red, yellow, and green colors can be distinguished from each other by them, though they cannot distinguish yellow from light gray. At any rate, a reliable estimate of the frequency of occurrence of congenital tritanopia cannot be made. The figure given in Table I (one out of a million males) corresponds to five cases reported in the literature[17, 23, 29, 41, 56] some of which might have been acquired tritanopia rather than congenital.

B. Acquired Color-Blindness

Acquired color-blindness (central or peripheral defect or scotoma for colors) occurs in all diseases affecting the central retina or its tracts in the optic nerve, the optic tract, or the optic cortex.

TABLE II. Frequency of occurrence of inherited visual systems.

Designation by number of components	Non-theoretical designation (v. Kries)	Percentage of the population that have these visual systems			
		Male		Female	
Anomalous trichromatism	Protanomaly	1.0		0.02	
	Deuteranomaly	4.9		0.38	
	Tritanomaly	0.0001		0.0000	
			5.9		0.40
Dichromatism	Protanopia	1.0		0.02	
	Deuteranopia	1.1		0.01	
	Tritanopia	0.0001		0.0000	
	Tetartanopia	0.0001		0.0000	
			2.1		0.03
Monochromatism	Total color-blindness	0.003		0.002	
Abnormal systems			8.0		0.43
Normal system			92.0		99.57

The most common disease of the central nervous system which causes central field defects (both for form and color) is multiple sclerosis. Several generalized non-infectious diseases cause optic neuritis with attendant loss of color and form discrimination. The most common are blood dyscrasias (pernicious anemia, secondary anemia, or leukemia) and deficiency diseases (B1 deficiency, so called "diabetic amblyopia," and optic neuritis of pregnancy). The most common occurrences of central color field defect are in connection with toxic amblyopia, and those toxins which most commonly depress the central (as opposed to the peripheral) field are:

Carbon disulfide—used in preparation of rayon, rubber, explosives, hides, insecticides, and wall paper.

Lead poisoning found in painters, plumbers, riveters, storage battery workers, and compositors.

Spinal anesthesia.

Sulfanilamide—may cause optic neuritis or hemorrhages into optic nerve.

Snuff, iodoform, and stramonium—rare cases.

Thallium—used in industry as a rat poison and a depilatory.

Tobacco-alcohol—the most common of all the agents producing amblyopia.

Toxic agents and disease affecting the conducting (transmissive) elements of the optical apparatus (nerve fiber layer of retina, optic nerve, and tract) are classically supposed to cause red-green weakness distinguished from deuteranomaly only by having poorer light-dark and yellow-blue discriminations. This defect becomes progressively worse until red-green blindness is reached which is distinguished from deuteranopia chiefly by its poorer light-dark discrimination. Finally total color-blindness results.

On the other hand, injuries (such as produced by syphilitic infections[26]) which primarily affect the receptive (rod-cone) mechanism show first a depression of the ability to make blue-yellow discriminations. Acquired tritanopia, unlike acquired red-green blindness, may become stabilized and be distinguished from congenital tritanopia chiefly by the memory possessed by the subject of his former yellow and blue sensations. Acquired tritanopia leads to total color-blindness only when progressive red-green blindness ensues; the latter, however, may of itself lead to total color-blindness[22] as noted above.

There is no therapy for acquired color-blindness since this is merely a symptom. The therapy is directed towards the underlying cause. The return of normal vision is usually by stages the reverse of those which characterized the disease.

In addition to acquired color-blindness which prevents the subject from seeing colors which are normally present, some mention should be made of chromatopsia which refers to the vision of colors which are normally absent. Erythropsia, or red vision, is the most frequent. It occurs normally after the eyes have been exposed to a very bright light, such as sunlight reflected from snow. Since in erythropsia the bright portions of the visual field are tinged with bluish red and the dark portions with yellowish green, the name is only half accurate. Erythropsia, however, is often a source of anxiety to a patient on the sudden access of light to the retina after a cataract extraction, iridectomy, or even when the pupils have been dilated by atropine. It is probably due to the prolonged and predominant red phase of the after-image.[54, 60] Cyanopsia, blue vision, may form a fleeting symptom after cataract extraction, probably owing to the previous influence of adaptation to the yellow color of the lens, since before extraction the short-wave light had all been absorbed. It also occasionally is a rare symptom in poisoning (as by digitalis) or in diseases of the retina and choroid, as also is (very rarely) ianthopsia, violet vision, and chloropsia, green vision. Xanthopsia, yellow vision, is said to be a somewhat more common symptom of jaundice and also occurs in picric-acid poisoning.

C. Color-Blindness of the Trichromatic Observer

Lest it be forgotten that chromatic vision is normal only under very special conditions, the following circumstances are listed under which normal eyes are color-blind:

I. *Indirect vision*,—vision in the retinal regions somewhat removed from the fovea differs from deuteranomaly only by reduced light-dark, blue-yellow, and form discrimination; vision in a more peripheral zone differs from deuteranopia only in these same ways; and vision in the periphery differs from acquired total color-blindness only by reduced ability to make form and light-dark discriminations.

II. *Insufficient size*,—a luminous area of a given brightness perceived by the para-foveal region may, by reducing its area sufficiently, be made to fail to elicit any chromatic color although still easily visible. For such areas the normally trichromatic para-foveal region becomes characterized by a monochromatic visual system, the type being indistinguishable from acquired total color-blindness.

III. *Insufficient brightness*,—the normal dark-adapted eye is in every respect functionally identical with that of the congenitally total color-blind.

IV. *Insufficient time*,—a luminous area may be perceived as brightness when exposed for so short a time that no chromatic color is experienced. Under these conditions, as in flicker photometry, the normal eye makes light-dark

discriminations only, the type of vision being closely like acquired total color-blindness.[62]

V. *Chromatic fatigue*,—a form of artificial color-blindness can be produced temporarily (for a few minutes) by flooding the eye with a high luminous flux of chromatic light. In addition to rendering the eye insensitive to red, green, blue or violet light, whichever is the color of the fatiguing light, there is a shorter positive after-image of this light. This could be described as temporary chromatopsia.

The ability to overcome these handicaps to chromatic vision renders one normal observer much more valuable than another. For many tasks, particularly war-time tasks, that observer is more valuable who is not troubled by chromatic fatigue, and who can distinguish correctly the colors of small, dim, briefly visible objects even though he "catches them only in the corner of his eye." It has been found that on the average anomalous trichromats are much more susceptible to impairment of their chromatic vision by these circumstances than are normal observers. For example, they are said to experience chromatic contrast effects much greater than normal which interfere with their correct perception of colors. Because of this average susceptibility to handicaps, there has been a disposition to disqualify all anomalous trichromats for tasks to which dichromats are unfitted. Thus, it is stated by v. Kries (p. 409),[28] "We are indebted especially to Nagel's investigations[36, 38] for light on this subject. Donders had long ago expressed the view that such persons had a 'dim sense of colour.' This indeed has now been thoroughly established; that is, the anomaly of the colour system (in the sense of having to make a different setting for the Rayleigh equation)[41] can be considered as an important and sure sign of 'colour infirmity.' "

And again (p. 421),[28] "From the practical standpoint, the thing of most importance, . . . , is that not only dichromats but persons with anomalous vision also are below par in a number of respects, and they are particularly unsuitable for railway or marine service. This, therefore, to a certain extent is the chief reason for improving the methods of investigation. The examination of these people is the right way of going at the problem of finding out all persons with abnormal colour vision and eliminating them."

There is a question, however, whether to paint all anomalous trichromats with the same brush may not unjustly disqualify certain of them for tasks which they are perfectly capable of performing. Thus, Köllner remarks (p. 515),[24] "From the foregoing it follows that red-green imbalance (rotgrünungleichheit), by which anomalous trichromats are characterized, plainly has nothing to do with the red-green sensation. 'Anomalous trichromasy' and 'red-green weakness' do not mean the same thing; by the former we have supersensitivity at least for one color, and on the other hand in spite of the absence of red-green imbalance there can occur a deficiency of the red-green sensation. Anomalous trichromasy is characterized by a 'constancy' of the red-green imbalance (see above) and is sharply separated from the normal proportions; the degree of red-green sensation on the other hand can vary widely and all steps from color-blindness up to the normal average can exist, indeed it can exceed that average. As to the color vision of anomalous observers, one can say in general with respect to their decreased red-green sensation relative to the normal that under favorable observing conditions they see practically as well as the normal, but under unfavorable circumstances they can approach the condition of the red-green blind very closely or even equal it."

These views are largely borne out by the findings of McKeon and Wright[32] who say, "The family of hue discrimination curves shows clearly how successive degrees of the defect are revealed in an increasing inability to distinguish different colours. The curves form a continuous series between the curve for the normal trichromat and that for the protanope as reported by Pitt.[42]. . The luminosity and mixture curves . . . show comparatively little variation among themselves, and there is some justification for deriving a mean curve for the 11 observers."

Köllner's statement is also borne out by Nelson (p. 687)[39] who states, "If the differences between the normal and anomalous hue-discrimination curves are taken as a measure of the degree of deficiency of the observer, then it can be seen that the other characteristics cannot always be treated as an obvious guide to the extent of the

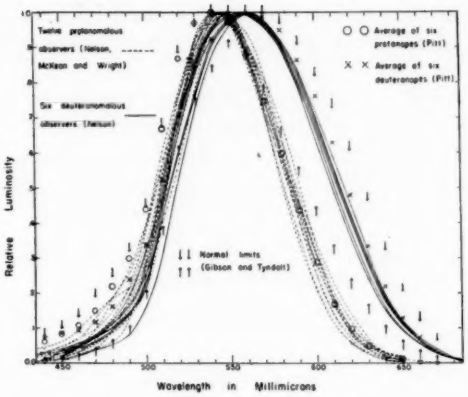
Twelve protanomalous observers (Nelson, McKeon and Wright)
Six deuteranomalous observers (Nelson)
Average of six protanopes (Pitt)
Average of six deuteranopes (Pitt)
Normal limits (Gibson and Tyndall)
Relative Luminosity
Wavelength in Millimicrons

FIG. 2. Relative luminosity functions of anomalous trichromats (6 deuteranomalous, 12 protanomalous) compared to averages for dichromats and to limits for normal trichromats. Deuteranopic and deuteranomalous luminosity functions fall generally within normal limits; but protanopic and protanomalous luminosity functions fall outside of normal limits.

defect. . . . This apparent discrepancy between the various characteristics is particularly noticeable as regards the position on the Nagel distribution curve (Rayleigh equation). For example, in the case of observers *A* and *D* . . . , *A* is farther from the normal on the Nagel curve, but his hue-discrimination is the more nearly normal."

The facts of protanomaly and deuteranomaly are therefore such as to raise the question whether this classification has very much practical value. After a subject has been found to be an anomalous trichromat, the question still arises as to what he is good for. This question is further touched upon in the discussions of tests, present and proposed, which are to follow.*

4. LUMINOSITY FUNCTIONS OF RED-GREEN-BLIND AND RED-GREEN-WEAK OBSERVERS

Figure 2 shows by dotted lines the luminosity functions of eleven protanomalous observers studied by McKeon and Wright[32] and one studied by Nelson.[39] It also shows by solid lines the luminosity functions of six deuteranomalous observers studied by Nelson.[39] Although at the short-wave end of the spectrum these groups of functions overlap and are not significantly different, the two groups divide quite sharply at the long-wave end. In this respect they are like the groups of functions representing the two corresponding types of dichromatic observer, the deuteranope, and the protanope. The circles represent the average of six protanopic luminosity functions evaluated by Pitt,[42] and the crosses represent his average of six deuteranopic luminosity functions. The arrows indicate the maximum and minimum values of relative luminosity found by Gibson and Tyndall[6] among their 37 completely studied normal observers. Although because of differences in experimental conditions no highly precise intercomparison is possible between the data shown for anomalous and dichromatic observers and these normal limits, nevertheless Fig. 2 indicates that the deuteranopic and deuteranomalous observers alike possess luminosity functions generally well within normal limits; but both protanomalous observers and protanopic observers possess luminosity functions that are abnormally low at the long-wave end.

Figure 2 tends to indicate also that protanomalous observers possess abnormally narrow luminosity functions even compared to protanopes; but because of the small number of cases this indication may fail to be significant. On this account in Table I the maximum of the protanomalous luminosity function, like that of the protanope, is given as 540 mμ, although Fig. 2 indicates that 545 mμ might be a slightly better value. The experimental conditions (field size, field luminance, surrounding-field luminance) and technics (adaptation, control of fixation, length of observing time) govern the participation of the rod mechanism in determining these functions. In any one study the luminosity curves may be thrown more or less to the short-wave side because of partial participation of the rods, either intended or inadvertent. The intertwining of the curves at the short-wave end is probably to be ascribed chiefly to individual variation of the amount of yellow or brown pigmentation of the eye media, such as degree of macular pigmentation.

Since from Fig. 2 both deuteranopic and deuteranomalous luminosity functions fall generally within normal limits, it is just as valid to

* See the other papers of this Symposium on Color-Blindness.

predict the brightness judgments of these abnormal observers from the standard luminosity function as it is those of a normal observer. Thus, for normal, deuteranopic and deuteranomalous observers alike, the relative luminosities of two colors specified by (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2) in the standard ICI colorimetric coordinate system,[10,20] may be judged by a comparison of Y_1 with Y_2.

For protanopic and protanomalous observers, however, colors which are red to the normal observer are significantly darker relative to other colors. Figure 3 shows that it is possible to deduct from normal luminosity a correction for the redness of the color and so arrive at a protanopic and protanomalous evaluation of luminosity. Instead of comparing the Y values, use should accordingly be made of the values of the function: $0.086Z+1.160Y-0.393X$. Figure 3 shows this function for the equal-energy spectrum compared to the upper and lower limits of 18 protanopic and protanomalous luminosity functions (6 protanopic functions determined by Pitt, 12 protanomalous functions determined by Nelson, and by McKeon and Wright). Since the tristimulus values, X, Y, Z, are known for many colors, the function $0.086Z+1.160Y-0.393X$ is quite useful; for example, the tristimulus values of the Munsell colors are known,[7,21] hence, by this function there can be determined with good validity which of any two surface colors of given Munsell notation will appear lighter either to a protanope or to a protanomalous observer. Such information is of assistance in the design of color-blindness tests.

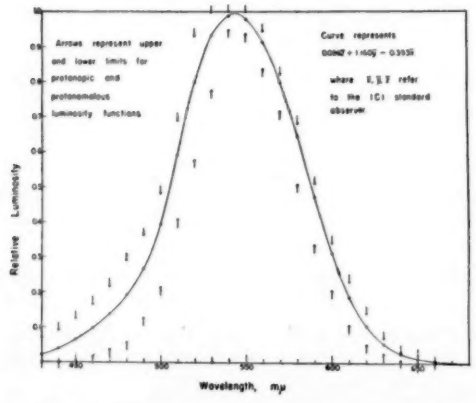
Arrows represent upper and lower limits for protanopic and protanomalous luminosity functions
Curve represents
where X, Y, Z refer to the ICI standard observer
Relative Luminosity
Wavelength, mμ

FIG. 3. Demonstration that a representative protanopic and protanomalous luminosity can be computed from the normal specification of any color. Instead of normal luminosity, Y, use $0.086Z+1.160Y-0.393X$.

Thus, it is seen that the facts of color-blindness are such that the brightness judgments of abnormal observers of the most common types may be conveniently predicted from the same color specification used for the normal observer.

5. CHROMATICITY CONFUSIONS OF RED-GREEN-BLIND OBSERVERS

The outstanding characteristic of a dichromatic observer which permits him to be distinguished from an anomalous trichromat is that although he makes important chromaticity confusions, he does not object to color matches set up by a normal observer between two fields of different spectral composition. On this account dichromatic visual systems are called reduction systems, and it is possible to derive from the normal specification of a color an adequate specification of the color for a dichromatic observer. With anomalous trichromatic observers, it is, of course, quite otherwise.

In 1855 Maxwell[30] pointed out from the Young-Helmholtz theory, how to define the chromaticity confusions of the color-blind in terms of the color triangle, now known as a chromaticity diagram. By this theory a dichromatic observer differs from the normal trichromatic observer by lacking one of the three primary color responses. The chromaticity for a dichromatic observer is therefore wholly determined by the ratio of the two remaining responses. For this ratio constant, there is defined on the normal chromaticity diagram, a straight line passing through the point representing the missing primary. A family of straight lines on the Maxwell triangle all passing through this point, therefore, represent by this theory all of the chromaticity confusions of the dichromatic observer.

Although the Young-Helmholtz theory is no longer regarded as a completely adequate basis for explaining color-blindness, this particular prediction from the theory was verified in a very satisfactory way in 1935 by Pitt.[42] Pitt found that the lines representing the chromaticity confusions converge closely on a single point, both for the protanopic observer and for the deuter-

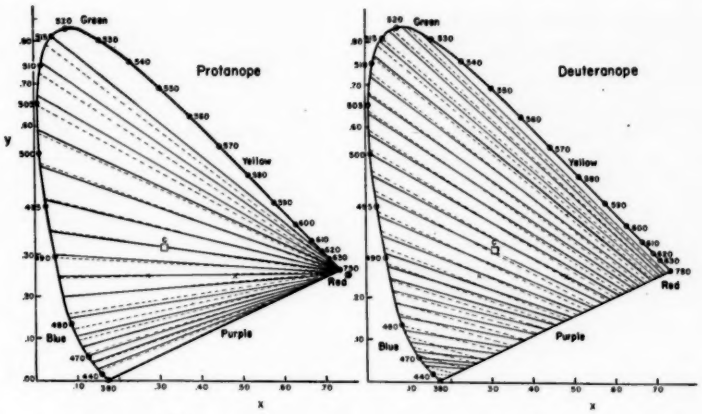

FIG. 4. Chromaticity confusions of the protanope and deuteranope (after Pitt). Note how closely the chromaticity-confusion lines (dotted) intersect at a single point for each of the two common types of red-green blindness. The solid lines included for comparison are co-punctal (protanope at $x=0.747$, $y=0.253$; deuteranope at $x=1.000$, $y=0.000$).

anope. Figure 4a shows as dotted lines on the (x,y)-chromaticity diagram of the ICI colorimetric coordinate system[10,20] the results of Pitt's determination for protanopic observers; and Fig. 4b shows similarly the results for deuteranopic observers. The families of solid lines drawn in for comparison pass through a common point in each case (protanope: $x=0.747$, $y=0.253$; deuteranope: $x=1.000$, $y=0.000$). The spacing of the lines has been adjusted by Pitt from his determination of chromaticity sensibility to wave-length change for dichromats so that the chromaticity represented by one line is just distinguishable from that represented by its neighbor. It may be seen that the failure of the dotted lines to converge to a single point in the case of the protanope is not significant, and for the deuteranope is scarcely significant.

As remarked by Pitt (p. 44)[42] these results together with the luminosity data just presented "are of the most fundamental kind for dichromats, and on such measurements are based, either knowingly or unknowingly, all colour-blind tests." It will be worthwhile, therefore, to inquire further into the interpretation of Fig. 4.

In Fig. 4a there is a confusion line passing nearly through the point representing ICI standard illuminant *C* (average daylight). This line passes through the spectrum locus at about 493 mμ. From this line it may be concluded that Pitt's average protanope will not be able to distinguish the chromaticity of illuminant *C* from that of the spectrum at about 493 mμ; that is, his neutral point is at 493 mμ as is indicated in Table I. However, the position of the neutral point is subject to rather large individual variations as is shown by Hecht and Shlaer.[12] These variations are to be expected because of the dependence of the chromaticity of illuminant *C* on degree of macular pigmentation, which does not affect the chromaticity of spectrally homogeneous light at all.

Similarly, from Fig. 4b it is seen that the average deuteranopic neutral point for Pitt's six observers occurs at about 497 mμ.

From this neutral point the red-green-blind observer sees yellow of increasing saturation up to a wave-length of about 530 mμ after which there is no further chromaticity change. In the direction of decreasing wave-length the dichromatic observer sees blue of saturation increasing to the end of the spectrum. Note how apt was Dalton's description of the spectrum: "My yellow comprehends the red, orange, yellow, and green of others; and my blue and purple coincide with theirs." We must take Dalton's purple to mean saturated blue.

This description of the spectrum fits both protanope and deuteranope, and we may ask how Seebeck[48] could deduce that Dalton was a pro-

tanope. This deduction follows from Dalton's further statement, "Woolen yarn, dyed crimson, or dark blue is the same to me." Assuming that the names, crimson and dark blue, have retained their meaning over the intervening 100 years, we may use Fig. 4 to check this deduction. Harvard Crimson[50] is found by way of the Munsell color system to have $x=0.48$, $y=0.25$; dark blue (Navy 1)[50] is similarly found to have $x=0.27$, $y=0.25$. These points are indicated on Figs. 4a and 4b by crosses. From Fig. 4a it may be noted that an average protanope is expected to confuse these chromaticities, since the points representing them lie on the same line; but from Fig. 4b it should be anticipated that to the average deuteranope crimson would appear as a brownish gray quite distinct from the appearance of dark blue which would be seen correctly.

Thus, it is seen that the facts of red-green blindness are such that the chromaticities experienced by such observers can be predicted from the same standard color specifications used by the normal observer. For example, the points representing on the (x,y)-diagram the standards of the *Munsell Book of Color*[35] are known.[7,21] Therefore, from the Munsell notation of a color may be obtained a reliable indication of its chromatic appearance to a red-green-blind observer.

6. SUMMARY

Color-blindness is of various types, and there is a greater or lesser adherence of groups of observers to these types. The most common are the two types of red-green blindness, protanopia and deuteranopia, and the corresponding types of anomalous vision, protanomaly and deuteranomaly. Although red-green-blind observers should obviously be excluded from occupations requiring the ability to make red-green distinctions, there is doubt what to do with an observer proved to be anomalous because in spite of the fact that many anomalous observers have virtually no ability to distinguish red from green, others do so nearly or quite as well as normal observers.

Color-blindness is usually congenital, but it may also be acquired as a result of injury or disease. Congenital red-green blindness and anomalous vision are much more prevalent among males than among females, and are regarded as sex-linked characteristics. Total color-blindness, however, is thought to be a simple recessive characteristic.

Red-green blindness is designated as a reduction form of normal vision because two lights of whatever spectral compositions are required to produce a match for the normal observer will also be indistinguishable by a red-green-blind observer. Red-green weakness, or anomalous vision, on the other hand, is called an alteration form of vision, because such matches by the normal are frequently quite unacceptable to the anomalous observer. In spite of this it is possible to predict the brightness judgments of the anomalous observer with good validity from the normal specifications of the colors being dealt with, the chromaticity alone being unpredictable. Methods of predicting precisely the appearance of colors to red-green-blind observers are described with a view to their possible usefulness in the design and development of color-blindness tests.

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Methodology in Test Preparation*

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SINCE this paper forms part of a symposium, in the other sections of which adequate historical consideration of the subject is given, I shall make no attempt to refer consistently to historical sources nor to specific tests. It has seemed valuable, instead, to summarize the general available information on methodology that is applicable to the problem of testing color vision so that previous and current tests may be evaluated in this respect on an adequate basis.

First, we need to inquire into the nature of tests in general. A test must not be confused with an experiment, which is distinguished by a very precise and limiting point of view. An experiment is basically non-utilitarian and therefore not constrained to get a certain type of results. The assumptions which it makes are self definitive and need take into account only the existing body of knowledge. Basically it consists of observations under conditions controlled by isolation, repetition and variation, so that preferably a laboratory is indicated, where meticulous attention may be given to details.

A test, on the contrary, is designed to perform a specific utilitarian job and the final criteria for judging it will be how well it does that job. We are inclined to believe, of course, that tests will work better if they are based on factual data, and if they follow good experimental methodology. Thus we are often disappointed when a casual judgment or a clever trick appears to serve the practical purpose as well as a more extensive group of test judgements. We can point to examples of this among tests of so-called "color-blindness." The concealed figures of the various pseudo-isochromatic charts are just such a clever "trick." I have used the expression "clever trick" advisedly, but there is no intention to derogate the brilliance of their invention nor the carefulness of the work that was necessary to make them effective. My point is that they do not measure, in any sense, a subject's color vision. They simply "catch" certain individuals who are unable to read them, and magnify that subject's perceptual deviation by appearing obvious to the majority of persons. They tell very little about the visual perception of those who fail, but they draw a sharp line between two groups of individuals—and that is exactly what they are meant to do. So long as we are content to accept the dichotomy, there is no need to seek further. However, the implied factuality of this distinction has frequently been questioned, and now, more important, its value is doubted. Even so, new tests will be examined by the same criterion. Perhaps what is wanted still is a dichotomy, but one with different practical implications, that is, one that draws its line of distinction at a different place and thus changes the relative sizes of the two groups. It may be more useful, however, to have a test that will yield a significant distribution of the population so that various dichotomies can be derived from it. In that case, appeal must be made to experimental methodology, for we have no evidence that repetition of the pseudo-isochromatic "trick" will give us a significant distribution. Obviously, then, test development cannot afford to "go it alone" in total disregard of experimental procedures. Indeed, it is safe to say that the nearer a test procedure approaches experimental conditions the more dependable will be the test results and the more satisfactory those results for practical purposes.

Nevertheless, practical considerations are primary in the sort of test which interests us. It is not necessary that we list exhaustively all such considerations, but there are certain ones that limit our methodology from the start. To begin with, practice usually demands that the test setting bear an obvious relation to the practical problem to which the test results are to be applied. This factor militates against laboratory techniques and apparatus that would otherwise make excellent tests of color vision. Precision instruments ordinarily require trained personnel to operate them satisfactorily, but for some

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reason it is supposed that anyone can and should be able to test for "color-blindness." Even the services are demanding a test that will be infallible in the hands of a "non-com" or a "C.P.O." In the case of the pseudo-isochromatic charts, acceptance is not general. Casually, to normal persons, it seems obvious that anyone who cannot read the concealed figures must have very peculiar vision, yet the individual who fails is usually unwilling to accept the evidence of his failure since he can discriminate the separate colors that make up the chart and often name them correctly. On the other hand, a matching procedure seems more reasonable and acceptable to both normals and deviates alike, because it corresponds more closely with the practical situations in which color vision is important. We have found this particularly true in the study of color aptitude at the normal and high ability levels.

A second factor of great practical importance for many applications of a color vision test is its time of administration. In situations in which the color capacities of a large number of individuals must be determined the time factor may be crucial. This means, inevitably, a sacrifice in precision so that almost every such test must be in some measure a compromise. Further, the form in which the test results are rendered may severely modify their utility. This is one point on which it would pay to educate the user of the test, difficult as that may be. The use of dichotomous or classificatory labels is as easy as it is unsatisfactory. "Color-blind" is certainly an erroneous label, and "deuteranope," "protanope," "tritanope," as they are ordinarily used, though more erudite are no less objectionable. Percentile ratings are much in favor, but they, too, should be used with caution and should be given more careful definition in particular cases. What can it mean, for example, to say that a man has 75 percent color vision, on the basis of charts read in one of the pseudo-isochromatic tests? There is the danger, also, of ascribing significance to the individual steps of any 100 unit scale even though the measuring device can be that finely read, when the object measured is much more grossly defined. Why measure an elephant's foot with a micrometer caliper?

Keeping these and similar practical considerations in mind, we may nevertheless emphasize our thesis that "adequate methodology is essential to competent color vision tests" and proceed to consider the controls that such adequate methodology implies. They fall, obviously, into the three groups, psychological, physiological and physical, but their interrelations and relative importance have not usually been made clear. I have stated them in the foregoing order to exhibit their connection to the problem we have in hand. Color vision is essentially and primarily a psychological problem. Any one who undertakes the study of any phase of it becomes to that extent a psychologist and, naturally, the more adequately he encompasses the current body of psychological fact and methodology, the better may we expect his contribution to be. I am not for a moment marking out preserves like a labor organizer, because many major contributions have been made to psychology by non-professional psychologists, but there is a direct relation between the extent and permanence of those contributions and the degree to which the contributors give psychological considerations their proper place.

Psychology recognizes the dependence of its data upon physiological organisms and upon physical conditions which impinge upon and affect the organisms. Therefore we must have in hand the facts of luminous emission and the facts of ocular excitation before we can undertake to map the procedure of our problem in vision. The order of consideration is not an order of evaluation. Every step is equally essential. This point must be emphasized, because too often a test fails from inadequacy in the psychological step. Physics does not see—its instruments give us only vibratory-corpuscular emission data. Nor does physiology have sight—only retinal-cortical excitations. Psychology, by way of its subject-instrument, has vision.

For the physical controls in a color vision test we must turn, then, to the physics of light, but we must bear in mind that we are not conducting an experiment in light. It is not our purpose, here to do more than indicate the general nature of the physical controls, but this brevity must not be taken as minimizing in any degree the basic importance of such controls. For test purposes, we may divide our available materials into three classes, namely, relatively homogeneous light

from a diffraction or prismatic spectrum, filtered light, and light from selectively reflecting surfaces. Each type of material has both advantages and disadvantages and our choice will depend finally upon a summation of these factors in which psychological controls and practical considerations play dominant roles. Probably the use of near homogeneous light gives us a degree of control and reproducibility that cannot be exceeded, if it can be equaled, by any other means. When we are engaged in careful experimental investigation of color vision, we may not be satisfied with less, but for test purposes, this material has distinct disadvantages. The essential instrumentation places laboratory limitations upon us, and to many who need to use color tests, laboratories and instruments are anathema. Practically, also, it is much more satisfactory and fruitful to be able to take your test to your population, than to have to bring subjects to your laboratory. These, of course, are not insuperable difficulties. From the psychological point of view, the limited size of the test field typical of a spectral instrument restricts the scope and validity of the test results. Even more objectionable is the dark surrounding field that is characteristic of an eyepiece instrument. Finally, the perceptual character of the aperture colors is disturbingly different from the normal mode of appearance of colors to the majority of persons, so that judgments on one material cannot be equated to those on the other without considerable practice, a requirement ruled out by test conditions. It is largely because of these factors that the trend of test development has been away from laboratory instruments.

The use of color filters, while not producing homogeneous light, gives us its equivalent, thanks to the psychological laws of color mixture and to the ICI data. Thus, without sacrificing accuracy we can eliminate some of the disadvantages of spectral instruments. There is no reason why the objections to size of field, to dark surrounding field, and in some degree to the perceptual appearance of the judgment colors, cannot be met. There still remains the fact that the filters must be incorporated in a more or less elaborate instrument. I know that to most of you, this criticism may seem absurd but the objections I have met in many quarters, have often been violent, and the acceptance of more "objective" materials by contrast has been enthusiastic.

It will be apparent from the discussion in another paper of this symposium of current and past "color-blindness" tests that there has been a distinct preference for reflecting materials—yarns, beads, papers, etc. We need not inquire into the manifold reasons for this preference, but they have accidentally or intentionally, been in line with the greater psychological advantages. Now that advances in colorimetry have improved the accuracy and facility of measuring colored surfaces, their major disadvantages have been removed. They remain dependent for precision, however, on the illuminant which is used, and the importance of this factor is not fully credited by the layman. The choice and production of reflecting materials for color test work presents the technological problems of permanence of the pigments, resistance to surface abrasion, reproducibility, and size of gradations. Recent experience has shown that all of these can be dealt with satisfactorily. Perhaps the factor of greatest advantage is the close perceptual similarity between such materials and those which enter into the practical situations for which tests are designed. This is important for a test, even though it gives no information concerning the nature of the visual defects in question and may often obscure such facts, but as I have said above, testing for visual divergences in a large population, which is the function of a test, cannot be substituted for careful laboratory study of vision. There is the further danger, in the use of reflecting materials, that they will be chosen casually on the basis of their appearance and without scrupulous regard for their physical reflectance characteristics. This point cannot be over emphasized! It is crucial to all further work and explains why the older yarn tests and some of the current "practical" tests do not give reliable results. On the other hand, the fact that lights of two different spectral distributions can be made to match for the normal subject may be one of the "tricks" that can be evolved into a color deficiency test. Already, it is being used as a test for a related problem.

Let us turn now to the physiological conditions that must be considered. Again we shall simply point out the factors that must be given detailed study with respect to every individual test.

Physiological optics must be a primary concern in our control of the conditions of excitation. Often the physical and psychological precautions will include the physiological, as for example, area of the test object raises the question of foveal *vs.* peripheral excitation, and pupillary control, the question of excitation intensity. There remain, however, such problems as innate *vs.* acquired color disturbances, the dependence of color vision upon systemic conditions, metabolic, toxic, etc., the interrelation of the photopic, and scotopic functions, the question of whether color deficiency can be improved, by vitamin feeding for example or by retinal treatment. The nature of the retinal correlates of color vision, normal and deficient, is always intriguing, but physiological hypotheses of visual functions may be more hindrance than help in working out an adequate test methodology. There is no question that in the past they have been a great motivating factor. Investigations to prove or to disprove particular theories have produced a wealth of factual observations, but in many cases, "theories" themselves have obscured the proper direction of attack for an adequate test procedure. The greatest fault in this respect is with the "Trichromatic Theory of Vision." I am not referring, naturally, to the laws of color mixture nor to the data on three color mixture equivalents to spectral colors. I am objecting, rather, to certain physiological and psychological inferences that have been made from such data and have been elevated to the rank of pseudo-facts. It is my own interpretation that as we learn more and more about the retina, the less evidence we have that its function is anything like as simple as a matter of three photochemicals. To this objection may be added the absurdity of trichromatic theory for psychology. As this specifically affects our problem of a color vision test, that theory has saddled us with the misleading terms "deuteranope," "protanope," "tritanope." If they are redefined to refer as Dr. Judd points out, simply to the three color mixture equivalents of spectrum colors for color deficient subjects, they may serve a useful function of comparison, but they must be divested of the implications of physiological explanation and psychological fact carried in the pseudo-descriptive translations "green blind," "red blind," "blue blind." Much more experimental work is needed from a psychological point of view before we can use legitimately such terms as these, and we shall be led astray if we take them as descriptive and allow them to determine our test procedure.

As I have indicated above, colors being primarily psychological data, a color vision test involves of necessity psychological procedure and after having worked out the physical and technical controls it would be folly to be any less precise psychologically. Yet the major criticism of many color vision tests is their casualness in this respect, apparently for no other reason than disregard of the available facts. For purposes of psychology, the human organism may be looked upon as an automatic recording instrument, like a recording voltmeter, or thermometer, or photoelectric spectrophotometer. Flash light upon its sensitive elements and you get reports of color. In the experimental laboratory, the psychologist must spend time and effort calibrating or training his instrument to a high level of sensitivity, accuracy, and stability. As a tester he does not train or calibrate, but takes the crude instrument as he finds it and attempts to obtain as precise a measure of its capacities and limitations as the situation permits. But the instrument is the same that he has struggled with in the laboratory and he knows, therefore, many of its limitations and vagaries, and may profit accordingly.

First of all, let us dispose of the fallacy that a visual test measures visual "sensations." One doesn't find "sensations" running around in the psychological laboratory or anywhere else. They exist only in textbooks and in the minds of psychologists as concepts which serve as reference points. Human instruments or observers or subjects perceive various phenomena and can report upon them by indicating the appropriate, carefully defined categories, e.g., red, yellow, blue, etc. In a visual problem the subject points out the color qualities present in a given perception much as a pointer moves along a scale. Obviously, the simpler his task the more steadily he will perform it. Thus, if he is permitted to say "this is like that," he will do better than if he has to say "this is red" and "that is green." If the report is still further complicated perceptually by requiring a number or a design to be read, additional factors are involved.

Since any test of vision presents the subject with a perceptual problem of some sort, such as matching, discrimination, recognition of form, etc., we must take account of the factors that enter into such perceptual patterns. Some factors can be dealt with in the planning of the test materials, some must be got at by way of the test situation, but a few are inherent in the organisms that are being tested and while they cannot be eliminated or controlled their presence and nature must be recognized and taken into account.

Size of the test object is important in any test, partly because it controls the physiological factor, the area of the retina stimulated, but as much or more because of its effect on the judgmental pattern. For this reason we cannot refer judgments on one area to equivalents at a larger or a smaller area. For specific conditions, comparative data have been obtained that bear this out, but for any other conditions they must be obtained empirically. In general, large areas improve discrimination, subject as one might expect to the Weber-Fechner law of "diminishing returns." Thus the National Bureau of Standards uses 4-inch placques in making certain surface color comparisons. Mr. Foss made the casual observation in the course of preparing the ISCC test materials that the large colored placques about a foot square showed much more obvious differences in the series than they did when they were cut up into inch-and-a-quarter by inch-and-a-half chips. As applied to our particular problem, one of my color-blind subjects who is a highly trained observer insists that a large area of red is obviously different from and, he believes, redder than, a small area of the same reflectance characteristics. On the other hand, using the ISCC saturation series of reds with normal subjects we have found that when the chips are masked down to two partly overlapping ($\frac{1}{5}$ circum.) disks of one cm diameter the same discrimination curves were obtained as with the full size ($1\frac{1}{4}'' \times 1\frac{1}{2}''$) chips. These results are not entirely unequivocal because the steps of difference in the series are all supra-liminal. Reduction of the area left them still supra-liminal.

Size unquestionably works against the ready acceptance of color test instruments using eyepieces and having, consequently, small judgment areas. A test which utilizes areas more in accord with those ordinarily perceived in practical situations has obvious advantages. In any case, we must not forget that a subject's visual field has a fixed size and that Hering's law of reciprocal spatial relations is always effective, *viz.*, every area of light or color in the visual field affects and is affected by every other area. It is essential, therefore, that a large area surrounding the judgment area, and in some measure the whole visual field, should be controlled as precisely as the colors under observation. The dark field of an eyepiece provides this control, particularly if it is used in a dark room. Such conditions, however, set up dark adaptation, altering the photopic-scotopic relationship in the retina, and changing the perceptual characteristics of the colors, which is highly undesirable. A preferable background is neutral or middle gray which need not cover the entire visual field, but should occupy a large region about the judgment field. Such a background must always be used if reliable results are to be obtained, and where possible should be incorporated into the test equipment.

Where test areas are juxtaposed, it is essential that the length of the lineal contact be kept constant, and that the line of demarcation be always the same. Again, these factors are fixed in most eyepiece instruments, but may be highly variable with reflecting materials. Their importance was brought home to us early in our work with the ISCC test. For reasons of production our chips are rectangular, and we found it necessary to specify the dimension which should be juxtaposed. It also proved best to use a minimum line of demarkation, even at the expense of increasing the ability to discriminate and thus reducing the sensitivity of the test. How this factor can be utilized in the opposite direction is demonstrated in Mr. Farnsworth's test.

The spatial arrangement, Right-Left or Up-Down, of a pair of colored areas affects the comparison judgments a subject makes of their appearance. In a long series of judgments on the same pairs, trained observers will show a considerable difference between the R-L position and the L-R, and between the U-D and D-U. With untrained subjects, it is much greater. The space error is individual and unpredictable, so that a fixed arrangement of two areas will favor some subjects and penalize others, in every case to a

different degree. For experimental purposes the space error must always be compensated by duplicating all judgments using both positions. In a test, such multiplication of data is not always possible, but its omission often invalidates any extensive statistical treatment. For certain purposes, it has been useful to make the judgment areas into annular rings, but this does not eliminate the space factor, and actually magnifies the difficulty when the area is fairly large, e.g., 10 to 20 cm viewed from one meter. Thus, when a disk of 10 cm is placed upon one of 20 cm one frequently gets four different judgments according to the radius upon which the observation is made. In our experience, the vertical dimension appears to give less space error than the horizontal, therefore, in the Aptitude Test we standardized upon that and obtained only up-down judgments. In another test where it was more convenient to use the horizontal arrangement we duplicated judgments in both positions, and we did not make the mistake of expecting the two sets of judgments to agree.

Fortunately, the time error does not enter, as such, into a visual test, but when a series of judgments from a number of paired stimuli is being taken, the final score may be influenced by the order in which the judgments are given. This may be due in some measure to the temporal effects in vision, *viz.*, adaptation and its after effects. Discrimination is not the same when you work through the spectrum from blue to red as it is when judgments are begun at the red end. A small difference may be judged "equal" following a larger difference and "different" following a smaller difference. The order factor cannot be eliminated but it can be stabilized, in a test, first by following a haphazard arrangement of stimuli and, second, by using the same order for all subjects. The relative values of the scores are thus freed from intra-serial effects.

In the discussions of the order of succession and of the surrounding field, we have indicated two needs for control of the whole visual field. In addition, a check must be kept on the absolute intensity of the general visual stimulation. Since we are concerned with color vision, there will be a lower limit above which we can depend upon the validity of our data. For practical purposes this lies considerably above the scotopic or twilight vision level. Vision, however, adjusts itself so readily that differences from 10 ft.-c to 100 ft.-c have given no significant effect in tests of discrimination. Some subjects have been found to protest at illuminations above 50 ft.-c especially of artificial illumination. Most, however, have found as high as 200 ft.-c of north daylight agreeable for close judgments.

How many judgments to require in a particular test is one of the most difficult questions we have to settle. In this we stand between the practical demand for brevity and the statistical need for an adequate sampling. The question of the number of judgments upon which a limen may be based has been discussed in the literature by Fernberger and Boring. For our purposes, the argument summarizes to "It depends," and we are left to solve the problem for ourselves. The answer in any particular case will depend on the type of judgment required in the test. If a test is based upon recognition of a more or less complicated pattern, such as the pseudo-isochromatic charts, multiplication of judgments adds little to the certainty of the test. However, sometimes repetition by means of charts showing different letters or numbers must be made to circumvent learning of the right answers. If one simplifies the judgment, more repetitions must be given. When the subject is asked simply to report "same" or "different," we have required of him the simplest and therefore the most stable judgment possible, but we shall need a larger amount of data from every individual. We shall probably find it necessary, also, to increase the variety of discriminations. We actually tried this procedure and found it unsatisfactory. For a test of color vision deficiency we needed to get not only discrimination, *per se*, but also a qualitative indication of the direction of the discriminated difference. It is not as stable a judgment, but we were after a test score not a discrimination limen.

Also, for test purposes, we found it advantageous to complicate the judgment even further by requiring it to be made in the form of a matching adjustment. Ordinarily, careful experimental procedure excludes the method of adjustment because it introduces uncontrollable factors that are extraneous to the judgment desired, but for test purposes this very complication aided in

bringing out the individual differences in which we were interested. I have already pointed out that we were not testing eyes, but *eyes in use*, i.e., visual perceptual aptitudes, and the success of such a test depends more upon the choice of the perceptual pattern than upon any other single factor. It is precisely there that the "trick" succeeds or fails. No general rules can be laid down, but I can illustrate the point by reference to some of our experience with the various forms of the color aptitude test. We asked for discrimination judgments, but it made all the difference between test and no test how these judgments were given. With a little training all of our normal observers could say accurately which of a pair was "redder" or could place the whole group accurately in an ascending series, but it was more difficult to match a duplicate series to the first when it was arranged haphazardly. However, too many subjects succeeded perfectly to make it a useful test procedure. Success came, finally, when one match at a time was required among a haphazard group. With subjects whose color vision deviates, the situation proves to be quite different. A group of only twenty chips, chosen of course to offer the confusions indicated by experimental results, presents a perceptual pattern of a complexity that varies with the degree of deviation. This gave us the type of distribution we sought. From it we can make the deuteranope-protanope dichotomy if we wish, because our materials were prepared with this in view, but the results also show that the confusions of one type are far from being completely distinct from the other. "Deuteranopes" make many "protanope" errors and "protanopes" many "deuteranope" errors. For once a test has given us a fairly precise indication of this particular aspect of visual anomaly. When additional materials are available the tests results will take on further psychological significance. I have cited our experience with this test to show the intricacies involved in selecting the type of judgment to utilize in a color vision test.

Closely connected with the type of judgment is the form of the instruction by which the task is set up for the subjects. Even the simple direction to "find the matching chip" can be taken in ways so different as to give widely divergent results. Test instructions must therefore, be explicit. They cannot be left to the discretion of individual testers, but should be presented in printed form with standardized directions. Sometimes a particular word may be useful in bringing out color deficiency by the very fact that it is equivocal only to such subjects. We found, for example, that the instructions to "judge the redder" of two chips, while it did not appear sufficiently precise to some normal subjects, because of the low saturation of the colors, was entirely equivocal to color deficient subjects who, on the other hand, had no difficulty in judging simple likeness to a standard red.

Learning is a characteristic of all human organisms and, consequently, is present in some degree in any test performance. The second ten judgments are likely to be better than the first ten. The effect can be minimized in various ways specific to a particular test. In many cases results may be stabilized by means of a practice series, but usually it is not valid to compare "test" with "retest." For most purposes, we require of a test that there be a maximum level of attainment beyond which a subject cannot go no matter how much he practices. In the ISCC aptitude test this is the case, and we found that speed of adjusting to the test requirements at the beginning, that is, practice, was a significant part of the test problem.

Finally, the general capacity level or intelligence of the individual subjects cuts across all psychological test results. It does not, however stand as a criticism of them. Tests of the sort we are discussing are tests of color vision in use, and eyes of equal physiological function in organisms of different intellectual capacity will yield different practical results.

Usually, a discussion of tests moves from this point into a consideration of the statistical treatment of data. We have already discussed the number of judgments in a test as it affects the practical problem of the time, and the form of the results required by the practical problem. We shall not pursue the important question of statistical procedures further, since there are ample treatises on the subject from which each experimenter can choose. Suffice it to say that such treatment of results is a necessary evil of all test construction.

SUMMARY

I want to repeat that in the preparation of tests of color vision the methodology employed is all important. Physics and physiology furnish the material conditions. This paper has been concerned with them only to point out their basic importance. It has seemed sufficient also simply to remind us that the utility of a test is a practical matter that will override many considerations of precision and accuracy. It has been our principal concern to emphasize that the essence of a test consist in the judgments by the subjects and that we shall have no adequate test unless the psychological conditions are properly controlled by a suitable methodology. A number of the judgmental situations met in a test of color vision have been described in some detail. While size, position, order, adaptation level, number and type of judgments, form of instructions, practice, capacity level do not exhaust all the problems of psychological methodology, they form a minimum of controls for any test of color vision.

Evolution of Color Vision Tests[1]

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THOUGH Sweden, Germany, England, France, Japan, and Russia each have their own distinctive color vision tests (Sweden the Holmgren wools; Germany the Stilling pseudo-isochromatic charts, the Nagel anomaloscope and color circle cards; England the Edridge-Green lantern and test cards; France the Schaaff mosaic diagrams; Japan the Ishihara; and Russia the Rabkin polychromatic charts), and though evidence from many sources favors distinct racial or regional differences in color vision in man (*1*),[2] the United States of America is still dependent upon borrowed and makeshift adaptations. It is even uncertain whether a single test adequate to gauge the color capabilities of mixed American stock throughout the length and breadth of the country could be devised. This does not mean that research workers here and there have not been alive to the need. In 1939–40 a pseudo-isochromatic test of an improved type, utilizing a design introduced by Jensen in 1936, sidestepping many of the objectionable features of the foreign charts and permitting ranking on three levels of ability, was projected by the writer. Permanent inks in suitable spectrophotometric ranges were, however, not immediately obtainable. Various other American projects are reported on this program.

A. ORIGIN OF CURRENT TESTS

Historically, the color vision tests now current have evolved under the triple stress of (1) the discovery of unique cases; (2) the launching of new theories and hypothetical categories of defect; and (3) pressure of emergencies such as great railway disasters, war, the invasion of industry by color, the need for prognosis in cases of local or general disease, or of guides in the study of heredity. The invention of new apparatus or materials, the Maxwell rotating disk and the spectrometer, gelatine and glass filters, daylight roundels, and the Munsell graded papers, has further accelerated research and test development.

The first cases of deficient color vision to engage the serious attention of science (those of Harris the shoemaker and his two brothers) were reported in 1776 to Joseph Priestley, author of a treatise on vision and color (1772) (*2*). Others followed quickly, Scott the draper and John Dalton, the well-known chemist, reporting their own imperfections of vision in 1778 and 1794 (*2*). Even in these early crudely tested cases, the stock traits of aberrant color vision came out clearly: blue and yellow as the sole hues retained; the light sense and general acuity of vision divorced from chromatic sensitivity and relatively unaffected; night vision usually good. Degrees of chromatic insensitivity were also noted, incidence among women being low, with deficiency usually mild. Even heightened color contrast appears in the observations, and the occasional shortening of the long-wave end of the spectrum; likewise the congenital and hereditary nature of the defect. The solar spectrum and a length of striped ribbon constituted the first test material. Sorting out of colors from a variegated mass of samples and matching were other favorite early methods.

At first no one except Dalton realized that the defects reported were anything but individual idiosyncrasies. The fact went unsuspected that actually they affected five to ten percent of the male population, representing a reduction system, a reversion toward a simpler type of eye with greatly reduced discriminations for hues, such as science has now discovered on the lower levels of evolution (*3*).

In the mid-nineteenth century, however, theory gave a new slant to testing, and large blocks of the population were presently examined. Helmholtz revived Thomas Young's physiological mixture hypothesis of color vision of a half century earlier. Nature, Young had suggested in 1801, was hardly likely to have wasted seven specific sense receptors on the spectrum colors

[1] This paper is part of a symposium on Color Blindness and Color Blindness Tests arranged for the March 4–6, 1943 meeting of the Optical Society of America by the Inter-Society Color Council.

[2] Italic figures in parenthesis refer to literature cited.

when three pigments, red, yellow, and blue, and their mixtures, suffice for the entire gamut of the artist's palette. Guided like Newton by analogies between light and sound stimuli, by the fact of forced vibrations (to account for intermediates), and a fancied parallel between the spectrum and the musical scale, Young at first linked his trineural mechanism with the artist's triad, red, yellow, and blue, the vibration frequencies of which are as 8, 7, and 6. Next year, influenced by Wollaston's diffraction spectrum with its prominent red, green, blue, and violet bands and reduction of yellow to a narrow line, Young shifted to another trio, red, green, and violet [see his *Lectures on Natural Philosophy* of 1807 (*4*)]. The corollary followed that color vision defects must result from lack of one of a trio of nerve fibers or photochemical processes. Red-, green-, and later violet-blindness, linked with insensitivity to the ends or middle of the spectrum, were therefore posited (though violet-blindness had been observed only experimentally with the aid of drugs), and tests began to be blocked out accordingly.

In 1875, following a shocking railway disaster in Sweden, that country took the lead, Frithiof Holmgren of Upsala developing a wool-matching test, more systematic than the old sorting ones, but handicapped by rigid adherence to *a priori* categories of defect, and an unwise choice of test and match skeins, as time has shown (*5*), (*27*), (*28*). Adopting unreservedly Helmholtz' tentative triune visual processes, and his early hypothetical red-, green-, and violet-blindness, abandoned or radically altered by the theorist himself in the second edition of his Optik (1890), Holmgren picked as standards to be matched for detection of the three types of color blindness three large skeins of a very pale yellowish green;[3] a purplish pink or "rose" (toward violet) representing a mixture of the end colors of the spectrum, red and violet; and a vivid signal red. Careful directions for the use of each are given, together with the reasons for non-equation of the chromas, but subsequent users usually ignore the instructions, and assume the three large skeins were designed each to test one of the three defects, shifting them about the spectrum accordingly.

Furthermore, confusing shortening of the spectrum with "red-blindness," Holmgren or his followers, reasoning by analogy, came to assume that in "green-blindness" green is not merely dulled but darkened. This error is perpetuated in colored plates of confusion hues, as well as in the keys to green matches, to the perplexity of examiners even today.

All this in spite of the testimony of many able color-blinds, Dalton and Dr. Pole among them (*6*) that they were neither red-blind nor green-blind, but red-green blind, seeing in the spectrum only blue and yellow in various shades, with at most a gray band in the green region (in the neighborhood of 500 mμ).

The Holmgren test was early adopted by railroads throughout northern Europe and America. Belief in three mythical types of deficient vision, no authentic case of which has ever been recorded to the writer's knowledge, was thus widely disseminated, persisting even today. It is noteworthy, however, that some of the Mediterranean races refused to accept the Holmgren test, based on the Scandinavian eye.

A German scientist, Ewald Hering, presently launched a different type of theory, based directly upon observed facts. Hering added green to Young's original triad of red, yellow, and blue (thereby arriving at Leonardo da Vinci's favorite basic four). These four primaries Hering linked in pairs, red-green, and blue-yellow, on the basis of half a dozen sets of observed phenomena—afterimage, color contrast, color mixture, peripheral field limits, invariability, etc. (*7*). Speedily out of this, the tetrachromatic or "opposites" theory, grew a more promising type of test, of the pseudo-isochromatic or "vanishing pattern" order.

In the meantime, however, some new and puzzling deviations from normal color vision had come to the fore, and given another slant to the test situation. As early as 1835 Seebeck at Berlin, interested in the industrial handicap, had discovered among his color-blinds a number atypical and unclassifiable in their responses, distinguished when tested with the spectrum by a loss both of color and light sensitivity in the long-

[3] In the Stoelting set used by the writer, copied directly from an original Holmgren, the first test skein is faintly yellowish, though Holmgren described it as a "pure green," neither yellowish or bluish. Differences in illumination, hue sensitivity, verbal usage, or divergent dyes and fading may explain the discrepancy. In some nondescript sets the red skein has a definite orange tone. The purple also varies, in hue and chroma.

wave end, in varying degrees (*8*). Rayleigh presently undertook the investigation of a handful of similar odd cases among so-called normals, who required varying amounts of red in an R+G=Y mixture (now known as the Rayleigh equation; carried out sometimes with lights, sometimes with reflecting surfaces and rotating disks). Two out of 23 he classed as red weak, five as green weak, the remainder, himself among them, as normal. Von Kries followed with just four cases—two normals, two aberrant—and on this sketchy basis launched two new categories with misleading Greek names, protanopia (literally blindness to the first primary) and deuteranopia (blindness to the second) (*9*). Nagel added protanomalous and deuteranomalous to characterize Rayleigh's two divergent groups.

Actually, the new fact discovered suggests a trend toward atavism, a reversion toward the more primitive night eye of our ancestors and of many animals. For along with relative insensitivity to long-wave stimuli (showing in both chromatic and light response) there is the Purkinje shift of the brightest strip of region back along the spectrum toward violet that is characteristic of night vision, perhaps a slight shift of the entire set of hue responses. Seebeck's and Rayleigh's discovery of scoterythrous vision,[4] shortening of the spectrum in the red, which may overlay normal vision or R-G deficiency, was probably what influenced Holmgren (who apparently confused it with hypothetical red-blindness) in his test set-up. By false analogy, in so-called "green-blindness" he and his followers assume a complete fadeout or a blackout of the middle of the spectrum.[5]

In the new Stilling pseudo-isochromatic charts, based on the Hering theory of four primaries, appearing shortly after the Franco-Prussian war, there is special provision for scoterythrous vision (Plate VII), also for the doubtful, semi-pathological blue-yellow blindness or weakness that had also come to the notice of science (Plate VIII). Hering, as above stated, assumes (instead of three) *four* primary chromatic responses, linked in pairs, blue with its antagonistic hue yellow, red with its opposite green. These hues (a slightly bluish red and bluish green) are antagonistic or opposite in the sense that when mixed, in their ordinary daylight intensities or reflectances, they will not combine to form an intermediate hue, as yellow, but neutralize each other. Further, each of a pair tends to induce a halo of its opposite on the adjacent area, or on the same area after its removal or extinction. Either chemical, electrical, physical, or neural factors would afford a basis for these phenomena. The fact that the basis is at present undetermined is unimportant. The usefulness of tetrachromatic theory in diagramming color experience as such in normal and aberrant cases is unparalleled, and gradually achieving recognition.

Guided by these new principles, Stilling of Strasbourg, about 1877, with the aid of a red-green blind artist and a blue-yellow blind teacher, worked out his vanishing pattern charts experimentally by disk mixture and matching. In his charts digits made up of colored dots or blotches of varying brightness and size appear on a field of dots in a confusion or interchangeable color (also in varying size and brightness). Reddish orange on dull yellows, and yellowish green on orange browns were first used to demonstrate red-green blindness; dull dark reds on dull dark yellows, red-green weakness. Reddish orange on yellowish red (on a pale yellowish red ground) tested blue-yellow blindness; medium red on light and dark browns (or low chroma yellows), scoterythrous vision. In the latter plate, as in some of those in later editions, Stilling's usual finesse in diversifying chromas and brightnesses in the digit hues as well as in the field is missing, hence the digit is too readily legible even with shortening of the spectrum.

The test has run through many editions (*10*). Lately Dr. Hertel of Berlin has taken it over, adding new charts, altering the old. Either he has not checked his plates as carefully as Stilling, or he has fallen back on the old Helmholtzian categories, or else he has adapted the test to the North German eye (whereas Stilling worked in the Franco-German city of Strasbourg in southern Germany). Incidentally, Hertel has utilized some of the clever variants of design exploited by Ishihara in which a figure (instead of disappearing) is transformed into another in the vision of the color deficient.

Other tests representing outgrowths of the

[4] A term first suggested by Rivers.
[5] See Burnett (*27*).

Hering theory, products of the psychological laboratory, set such tasks as *serial arrangement* and *hue classification*. In the last fifteen years Myers and Pierce (*11*) in England, Murray, Terman, and Farnsworth here (*12*) have used these methods; Spry of the Munsell Color Company also in his Student Charts. The subject is required to work his material into something resembling the continua that make up the color solid (whether double cone or pyramid). Derived also from the "opposites theory" are the tests that make use of the law of color induction (color contrast and complementary colored after-images), Cohn's letters in gray on a colored ground (1878–1905), Wiltberger's horizontal color strips and choice of vertical matches (1941).

Ophthalmology, under pressure to measure progressive acquired disability, has devised perimetric and hue threshold tests (*13*). The application of the Gaussian curve of error to the frequency distribution of biological traits by Galton and Pearson and World War I led R. A. Houstoun of Glasgow to undertake long-needed tests on unselected groups of the population. Trying out Rayleigh's suggestion that deviation in the Rayleigh equation (the amount of lithium red that must be added to thallium green to match sodium yellow) might be a matter of normal variation, Houstoun devised new tests of red sensitivity, and on groups of 5–600 reported that von Kries' and Nagel's set-up of opposed and clear-cut classes (protanopic and deuteranopic, protanomalous and deuteranomalous) in color-blinds and normals (the former based originally on four cases) was the result of discarding intermediates. Darkening of the long-wave end of the spectrum is in part normal variation (protanomaly), in part perhaps a general lowering of neural sensitivity (protanopia), a step toward twilight vision or toward total color blindness, with innumerable degrees or gradations of sensitivity in either form. Houstoun as a result of his investigations abandoned Helmholtzian premises, and substituted direct measurement of long-wave sensitivity for the equivocal and time-consuming Rayleigh equation (*14*).

The development of color printing led C. S. Myers and W. Pierce of the National Institute of Industrial Psychology in England in the 1920's to devise an industrial test utilizing serial arrangement or matching of red, yellow, and blue chroma series of lacquered disks, the revision and scoring of which was prolonged over several years under a Rockefeller grant (*11*). The Lovibond color glasses in 20 chromas, the Glenn Colorule (blues which range in one series to yellow, in another to green, with great change with altered illumination), and the I.S.C.C. Color Aptitude Test represent other outgrowths of industrial needs (*15*).

B. CLASSIFICATION OF TESTS

During the last 75 years, under pressure of rapid transit and modernized warfare problems, hundreds of tests have been evolved, though the perfect all-purpose test is as yet undiscovered. Those current today may be classed (1) according to stimulus media employed (reflected or transmitted light); (2) as photopic or scotopic, according as daylight or dark adaptated eye is used; (3) as individual or group; (4) by scoring method, qualitative or quantitative; (5) by response, according as simple or complex mental operations are required, or motor or verbal responses stressed (*16*).

(1) Tests may be classed according to the stimulus media employed (transmitted or reflected light). Besides spectroscopic light and filters of known transmission, standardized papers are available, formerly the Hering, Heidelberg, and Engelking for perimetry, today the Munsell, Ostwald, and others (*17*).

(2) They may be scotopic or photopic, utilizing the daylight or the dark-adapted eye. Too often there is no exact specification in the records. More daylight tests are needed, using precise control of transmitted as well as reflected light.

(3) Tests may be individual or group. Examples of the latter are the Podesta wall charts of 1916, Westcott's lantern slides of the Holmgren wools, Berens and Stein slides of some of the pseudo-isochromatic plates (*18*). Apart from the difficulties of Kodachrome reproduction, standardizing of the color temperature, or spectral energy distribution of the source, and the doubtful ethics of unlegalized use, all group tests involve distortions of perception. They may serve to single out a few cases for further examination but the scores of those in front and rear rows will not be comparable. Variation in visual angle means

also encountering such differentiated retinal areas as fovea, macula, red-green-blind zone, blue-yellow blind, optic disk, and possible scotomata. Deception is also less easy to control.

A gelatine filter lantern projection test of the vanishing pattern order using Landolt's broken circle in solid color on a solid ground has been prepared by MacAdam (this program). The opening of the circle may be rotated to any position, and the hue to brightness of ring or ground varied to a match. The number of discriminable hues in the color continuum may thus be determined, as well as "confusion colors." Color mixture equations, e.g., the amount of blue to be added to red to match gray, for the ordinary red-green blind, and the range of deviation should also be obtainable by this method, within the limits of available color filters. But for color blindness tests the design lacks the flexibility of the mosaic type of pseudo-isochromatic pattern which allows in a single plate for individual differences in luminosity function by latitude of brightness of the dots.

For rough screening work in small classrooms, an improved replica of the Holmgren sorting test with 6–8 standards instead of 3 [P, B, BG, G, Y (dull), R and R tint, Gray], and 36 variants in chroma and brightness of the standards (along with intermediates) has been used by Murray to isolate R-G blind and R-G weak. The 5″ standards (roughly equated in brightness and chroma to minimize use of secondary criteria) and the 4″ matches are displayed in wall charts on a neutral wall. A cross-section self-recording blank is provided, and the score is quantitative, the best subjects rating three times as high as the lowest. With this test two color-blind, two color-weak and one borderline have been isolated in a high school art class of 50, results checking with Ishihara, Nagel, and others. This resembles Snyder's and Terman's hue classification tests and may be given or repeated individually with a smaller set.

(4) Tests vary also according as the scoring is qualitative, with subdivision into totally color-blind, R-G blind, B-Y blind, scoterythrous (protanopic), etc.; or quantitative, with numerical score indicative of discriminative ability or sensitivity in certain ranges. General practice in scoring the qualitative or differential tests is not uniform, some examiners taking (mistakenly) an all-or-none stand for a pass (as in the Ishihara), others allowing 25 percent error. None of the pseudo-isochromatic tests were planned for quantitative scoring at the outset, certain digits were designed to be *visible*, others to be *invisible* to a certain type of disability; other patterns were planned for other defects or degrees of deviation. The plates with digits are not equated in difficulty, and for five years or more under war conditions the color printing of the Japanese and German plates (always a difficult matter) has been less uniform in successive editions. The verdict "pass" or "failure" has validity only when rendered by an expert examiner.

Quantitative ranking is possible in a wide variety of tests, though it tends to obscure types except in specially designed differential tests, such as those for chroma threshold, or luminosity. Such scoring alone, however, makes possible the distribution curves for large segments of the population, normal, and deviate, needed to establish the fact that the old stereotyped groupings, such as protanope and "proteranomalous," are too rigid, the matches and confusion colors deduced from them for test construction too narrow.

Much of the scatter on the quantitative scoring of any given test, as Houstoun has pointed out, is probably due to secondary causes inherent in the method, e.g., slight deviations in reflectance, hue-adaptation, timing, failure to grasp instructions, lapse of attention, etc. It is doubtful whether any ranking finer than quartile or quintile position in the group is valid, or any correlation except by the rank method feasible. An excellent example of quantitative scoring and a reasoned method of obtaining total scores from certain pseudo-isochromatic tests for use in figuring correlations is given in Philip's series of studies (*19*). His card sorting test by *color mass* (the numerical predominance of chroma-equated R, P, B, or G spots on a white card), with three trials, for groups of four to six hundred yields a range of scores fitting a normal curve and allowing decile rating. While planned primarily for use in psychometrics, the test could readily be adapted to the detection of the color-weak in certain ranges, especially if time scores are included in the rating. The Nela wool matching test also

yields numerical scores, but failure to rule out secondary aids (chroma and brightness clues) invalidates them. Edridge-Green with his card test (vanishing pattern) and color perception apparatus attempts to grade the individual directly as monochromic, dichromic, etc., to heptachromic (*20*).

Examples of self-recording tests are Jennings' adaptation of the wool test, Murray's hue classification, and the I.S.C.C.'s projected single judgment test, using R and pR chips in pairs of fixed chroma difference, with electric button recording. Self-recording blanks and devices all encounter the hurdle of low intelligence, and difficulty in following instructions. Jennings' record sheet was often inserted wrongly, Murray's required understanding of "under" and "opposite," prepositions in the use of which children of foreign-speaking parents invariably experience difficulty.

(5) Tests may be grouped further according to the type of response exacted of the subject, with emphasis predominantly on verbal or motor aspects; or on mental processes of varying complexity. The first group range from Hess' pupilloscope registering the effect of chromatic stimulation on the iris muscle, through Edridge-Green's lantern, calling for correct naming of colored lights under many permutations, his bead-sorting (requiring manipulation of materials), to Roaf's reproduction of design in paints or crayons, or the adjustment of rotating disks or spectrometer screws to a match. Clumsiness or embarrassment and other factors must be reckoned with, often offsetting the aid to attention of a definite manual or verbal reaction.

The mental processes involved may take the form of (a) a simple judgment such as the presence or absence of a given hue in chromatic threshold, color contrast and after-image tests, or in the Nagel cards; or the recognition of a hue in bead-sorting. (b) Judgment based on a perceptual field, as in the Philip dominant color test, or in the "vanishing pattern" charts. The latter, maintained at a fixed distance, does double duty, testing color discrimination and substituting roughly for perimetry; for constriction of the color fields in the color weak, or central scotoma from tobacco neuritis, will hamper legibility of a digit or design, especially if speed is kept constant. (c) A third type of response is of a higher order, conceptual or analytic, though often confused with simple judgment. It presupposes ability to analyze color experience, and abstract brightness from hue or chroma, chroma from brightness or hue, or hue from either, an ability that even trained scientists may lack. E.g., the physicist, preoccupied with transmitted light, often fails to recognize chroma as distinct from brightness. Inability to make these abstractions renders many instructions "Disregard brightness and match by hue solely" (as in the Nela) futile. The experimenter must equate chroma and brightness (as nearly as possible for atypical subjects) in order to clear the stage for hue judgments.

Ability to make these abstractions of a higher order is assumed in tests based on the psychological solid such as serial arrangement of chroma, hues, and brightnesses, or hue classification. (Pierce's industrial chroma series test, Murray's twenty-hue circle, Farnsworth's hundred-hue.) Untrained normal subjects make on matching tests many of the mistakes of color deviates, from sheer inability to analyze out hue from their integral color perceptions, classifying pinks with yellows, while refusing to sort fawns and browns with the latter, luminance rather than hue dominating their unanalytical color perception.

The above five test groupings are all more or less superficial, based on methodological factors —physical, physiological, psychological. A more significant classification is (6) by purpose. The aim, broadly speaking, of all color vision tests is either theoretical and exploratory, or practical and prognostic. The former group for the most part rely on the use of spectrally homogeneous light, the precision of apparatus controls and laboratory backgrounds. The latter are frankly utilitarian, designed (a) to screen out the dangerously aberrant in transportation systems where recognition of signal lights or judgments on terrain are vital, or (b) prognostic, with a view to diagnosing defect, and recession or progress in clinical cases—testing, e.g., chromatic deterioration in disease or toxic conditions, and the success of remedial measures (use of drugs, vitamines, practice with colored filters).

The two groups, theoretical and practical are, however, not mutually exclusive. The first or research group acts as feeder for new short-cut

practical tests; while each of the latter becomes valid only by checking against results obtained by more accurate and thorough research methods, applied to sizable control groups of normals as well as deviates.

C. THEORETICAL AND EXPLORATORY TESTS. RETROSPECT AND PROSPECT

The older tests were based on the physicist's spectrum, and such research problems as the determination of the limits of the spectrum, the position of neutral bands, location of the brightest hue in the solar spectrum, the number of discriminable hues and the mixtures by which each region may be matched.

Latterly efforts have been directed rather to determining what has happened to the psychological color solid in the various types of defect: e.g., the number of hues of equated chroma retained on the perimeter of the color square; the chroma thresholds for the four stable hues; the number of discriminable chroma steps in R, G, B, and Y as compared with those for the normal eye; the relative brightness of these hues in the deviate's solar spectrum.

Other research problems include perimetric determination with standard colors or lights (*21*) of the limits of each color field in aberrant vision, and the location of possible scotomata. Measures of hue, chroma, and speed in color contrast and after-images, of recognition memory for hues, determination of paired confusion colors for different types of deficiency, have also received attention and demand more, by the methods now in use for normals (*22*).

The exploratory research which provides the soil out of which short-cut practical tests must be evolved is, however, as yet utterly inadequate, as both the Scotch physicist Houstoun and the British industrial expert Wright have recently pointed out (*23*). A vast amount of work on sizable groups, not single individuals, laboratory "standard observers" or "typical" protanopes or deuteranopes, remains to be done before even the colors necessary for an all-purpose screening test can be selected.

This was brought home to the writer by the discovery in 1928 of an atypical deviate retaining only the hue yellow, along with a normal black-white-gray continuum, and no pathological symptoms. Though reported as a case of achromatopsia, examination disclosed a spectrum with an extended chromatic area in the region of the sodium lines, thinning out into the green and red regions of the normal. Search of the literature for an analogous case (to the extent of several hundred references in the intervening fifteen years) has afforded convincing proof of the inadequacy of recorded research on either normal or aberrant color vision as a basis for classificatory tests. This holds for procedures, apparatus, recording, and number of cases on which conclusions are based.

Experimenters fail to record or standardize the state of adaptation of the eye, scotopic or photopic, to take account of the brightness contrast induced by the black surround of an instrumental eyepiece, or of retinal rivalry from the unused eye (an intermittent clouding of the field). In the few experiments conducted with the surround illumined, specification of the amount (footcandles) or spectral composition of the illumination is usually omitted. Ordinary yellowish mazda is reckoned as "white light," or "sensation white" of unknown spectral composition is substituted for the solar beam, rendering many comparisons invalid. Shortening of the spectrum at either end is highly significant in color cases, yet the wave-length record is meaningless unless the stimulus magnitude is also recorded. An artificial pupil standardizes data, but records in terms of an equivocal "photon" may be misleading.

Omission of specific record of stimulus magnitudes renders reference to spectral region by wave-length virtually useless to the careful experimenter. Owing to the Bezold-Brücke law (shift of hue with constant wave-length but variable intensity, little understood but probably related to the different physiological levels of the red-green and blue-yellow limens), all color stimuli but the four stable primaries G, Y, R, and B, appear as slightly different hues at different intensity levels; e.g., 525 $m\mu$ (slightly yellowish green at moderate intensities) in the lower intensity ranges simulates 500 $m\mu$ (pure green) for the average eye. Similarly, 620 $m\mu$ (reddish orange) at lower intensities simulates pure red, at higher a yellowish orange.

The complex geography and topography of the retina (fovea, macula lutea, color zones, optic disk) are customarily ignored, and visual angle or

distance unrecorded (the latter important because the near-sighted eye favors red, the far-sighted blue). Chroma and brightness, or chroma and hue, are not differentiated (accounting for some of the discrepancies in hue discrimination data). The swift onset of fatigue (local adaptation and contrary hue induction) especially with transmitted light stimuli, hence the need of timing and spacing observations, is usually overlooked.

Instructions and test materials fail to take account of the deviate's reliance on brightness and saturation clues rather than hue, e.g., his tendency to substitute "darker" or "more vivid" for "redder," in directions, hence the need of equating brightness and chroma in paired hue comparisons.

Convinced of the great variability of color deviates, the difficulty of fitting them into the "classical typologies," and the need of modernizing and standardizing equipment so that observations may be repeated in widely separated laboratories, with no great financial outlay, the writer secured in 1932 a gray room equipped with Corning daylight lamps, spectrometer, adaptometer, perimeter, neutral and color filters and a set of Munsell papers as a basic outfit (*24*). No photo-cell photometer measuring light accurately to hundredths and thousands of a footcandle is, however, commercially available. Colored filters transmitting only the critical band, 500–510 mμ, and low chroma papers, especially in the yellows and the blue-greens are also unobtainable for research.

On the experimental and research side there are needed: (1) calibration of the spectrum in terms of the four stable and invariable primaries (two in the case of the deviate) a task left unfinished by the late Gosta Grönberg (*25*);[6] (2) a table equating the 40 Munsell hues by direct observation with color patches in a standardized Nela ribbon filament spectrum (restored to the relative intensities of the solar beam); and (3) distribution curves for the normal eye for hue thresholds and limits of the color field, secured with standardized stimuli.

[6] Schrödinger has shown the connection between the 3-components and the 4-components theory of vision, and Judd has given ICI equations [Ill. Eng. **36**, 3 (1941)]. D. N.

D. PRACTICAL TESTS: EVALUATION OF TYPICAL EXAMPLES

These may be *screening* or *differential* tests. In the first, designed to segregate the dangerously aberrant from the normal in the interest of public safety, economy of time and materials, and fairness (with reference especially to low mental levels, and the wide diversity of defects) are essentials. Differential tests should be adapted to the specific vocational situation and checked against ability in it. No test of either type is validated purely by theory, or mathematical calculation of "confusion colors" from the color-mixer's triangle. Reliability must be proven through mass application and correlations.

Desiderata

In rough-and-ready short-cut screening tests for gross defect and mass results, (1) *economy* demands that total time consumed lie within five minutes, that materials be standardized by spectrophotometric tests (not by the normal eye alone), reproducible, durable—resistant against soiling, breaking, marring—easily manipulated, and portable (*26*). (2) *Fairness* (in view of the wide range of mental ability and color discrimination) implies the set task be simple (suited to mediocre intelligence), with enough variety and appeal to evoke concentration and effort, in short pulses of attention. Items should be sufficient in number and range throughout the spectrum to tap variations in chromatic and luminosity functions, and fairly equated in difficulty. Set-up must be predetermined, so arranged as to eliminate involuntary suggestion from the experimenter (of the "Clever Hans" pseudo-telepathic type); with surroundings neutral, illumination controlled. Visual angle should probably include a paracentral area. Time should be limited, distance constant. Viewing should be binocular (except in rare cases) with vision corrected for gross myopic or astigmatic defects. Instructions to subject must be precise, unambiguous ("foolproof"), rigidly adhered to; if illustrations are permitted they should be standard. Scoring directions should be unambiguous as to latitude in responses credited with a pass. Test should be accompanied with a table showing in detail percent of correct and of atypical responses on

each item for mass results. Obsolete and cumbersome descriptive or theoretical categories should be eliminated. The color tester should be familiar with the deviate's tendency to rely on chroma or brightness in judging reds and greens and with the fact that the critical reds and greens are not the slightly yellowish tones of the dyer and popular speech. He should also understand devices for detecting simulation of normality or deficiency.

Differential tests for special vocations should be adapted to special needs as to materials, optimal illumination, region of spectrum of importance, degree of accuracy desirable, size of field and fineness of patterning, distance, etc.

Evaluation of Current Screening (and Differential) Tests

These may be subdivided according to the task set, into Sorting, Matching, Naming, Discrimination, and Sensitivity (Recognition), Arrangement, Reproduction. But these functions overlap, the subject, no matter how carefully instructed, may transfer the task from one head to another by "self-instruction:" e.g., in the Holmgren wools his decision, "That standard is probably green, I'll pick everything I've ever heard called green" produces results sometimes satisfactory, sometimes amazing.

I. Sorting Tests. Holmgren Wool Test and Modifications

In standard form, as issued by a reliable firm, this consists of 125 small skeins dyed with permanent dyes in various shades and chromas; and three large standards or test skeins—pale yellowish green, pale rose or purple (toward violet), and vivid red (in Munsell notation roughly 5GY 7/6, 10P 6/8, and 2R 4/16) (*27*). Many variations are available today. Stoelting's 1931 catalogue described 5 different sets called Holmgren, as well as Jennings, Oliver, Thomson, and Whipple modifications. The Army and Navy form, that adopted by the American Ophthalmological Society in 1901, and the Whipple modification all consist of 125 small skeins with larger test skeins. Thomson's variant, favored by railroads, uses forty small skeins only—an inadequate assortment.

The procedure as outlined originally by Holmgren calls for a black background, moderate lighting, and allows *one minute* for the total test, with the examiner counting 1, 2, 3, etc., as the subject picks 8–10 matches for each standard (thrown down one at a time, one or two feet beyond the pile of skeins), and tosses them down beside it. It is doubtful if any examiner holds to this method today, or secures the typical results predicted by its originator, or figured in his colored plates. Holmgren himself used the weak green skein first for a general diagnosis, with provision of 10 "pure greens," deviating neither toward blue or yellow, for matches. If the candidate made no mistakes he was judged normal.

If tan, drab, or a red match were chosen the test was continued, first with the purple, then with the red skein. Holmgren himself recorded three degrees of defect: 2, 1, and 0.5. He also fully recognized the complications introduced by unrecognized acquired or pathological cases.

The test is the favorite of borderline, color-weak, and even color-blind cases. The vivid dye colors, large visual angle, and peculiar luminosity relation of the three standards, which appear yellowish or fawn, bluish, and brownish, respectively, to the average deviate, often permit him to succeed through the use of secondary criteria (chroma and brightness doing duty for hue). Either directly or after a little practice off the scene, he learns to avoid doubtful skeins, selecting near-identities only. Long ago, U. S. Navy and Public Health officers exposed the weakness of the method, which let many deviates slip past as normal, yet tripped nervous color-capable, dismayed by the mass of 125 variants to select from, straining to discover all with the faintest trace of green or rose or red (*28*).

While the Holmgren wools did yeoman service in early railroad days in northern Europe and in America, picking 4 to 5 percent of color defectives out of thousands of railway employees (largely by a much simplified method introduced by Holmgren), its inability to segregate another 4 percent of "color unsafe" has been recognized in Great Britain and on the Continent for more than fifty years. Its failure to meet United States requirements today is patent along four lines. First, there is no uniformity of procedure, either in total number of skeins or their color specifica-

tions, in the hue of standards, number of choices required, directions, or timing. A pass in one examiner's office, failure in another, is not uncommon. Secondly, the relatively large masses of solid color permit cases of central scotoma (from tobacco amblyopia or other cases) to get by. The skeins become soiled or faded.

Most damning of all, the instructions are based on an erroneous and misleading set of categories. For Holmgren accepted literally the Helmholtzian theory in its original form (abandoned shortly by the physicist) selecting his three standards as earlier indicated to spot green-blindness, red-blindness, and violet-blindness. If retinal processes paralleled those of the industrial color matcher's colorimeter or mixture apparatus, it would be fairly simple to bait the test trap with yellowish red, yellowish green, or violet (a hue for each corner of the trichromatist's triangle), and catch and classify three types of defectives accordingly. The matter is less simple. Cases do not run true to Holmgren's prediction (whether they ever did in Sweden, with Nordic eyes, is in doubt). Confused by the directions and the three fictitious types of defect one examiner may pronounce the candidate green-blind, another, on the same evidence, red-blind (*29*), and when experts disagree it is customary for the court to dismiss the case against the candidate and pronounce him color normal (as in the famous British case of Trattles and Ettles).

Even the later categories, deuteranopia and protanopia, define and describe their type cases too narrowly. Actually the neutral bands in the green for the two are not invariably confined to distinct yellowish and bluish regions, respectively (525 and 496 mμ), but overlap, as Hecht has indicated (*30*). Certain examiners have accordingly shifted standard 1# from pale yellowish to pale bluish green—doubling the chances of error in the matches, and rendering comparison of scores from different offices invalid.

As a matter of fact, by increasing the number of standards to 8 or 10, an expert examiner can learn much of the color system of the deviate from the set-up of 125 samples, detecting even the added complication of shortening of the spectrum. In addition to Holmgren's three test skeins, Collins used pale blue, vivid blue, vivid yellow, fawn, and brown in her intensive study of ten deviates with a dozen tests (*31*)—a combination found useful by the writer also, with an added reddish purple. The test should be revised and standardized on this basis as an aid in diagnosing the accepted categories of defect or discarded. Only an experienced examiner should pass on the results. Nor should merely naming the red and green test skeins be accounted as having passed the Holmgren. If the number of test skeins is increased, the danger of infecting the minds of the examiners and the public with the notion there are only three critical areas in the spectrum is decreased.

Among the many devices proposed to prevent handling and soiling of the wools and reduce visual angle is the Jennings self-recording color perception test, utilized by the United States in World War I, still in use by railroads. Small areas of 68 skeins (greens and the assumed confusion colors for green) are exposed in one 12″×12″ compartment; 68 reds and confusion colors for red in a second (concealed). Green and red test skeins are shown in turn. Perforations, a stylus, and a record sheet slipped under each compartment allow the candidate to record his choices [see Stoelting (*27*)]. The scheme, however, is too cut-and-dried, adheres too rigidly to the obsolete Helmholtzian categories. Normals may fail, malingerers pass through memorizing of the two key patterns [see G. L. Collins (*28*)].

There is also a Nela version, with skeins arranged in 24–48 triplets, a test skein between a comparison pair. Failure to equate the luminosity of the three apparently affords secondary and misleading cues, as the numerical scores fail to check against other criteria of ability, and an unprecedented percentage of women are pronounced deficient (*32*). This test was recently used in connection with an attempt to improve color discrimination with vitamin A dosage.

Edridge-Green Bead Test

Hue identification, though no oral naming to disturb the tongue-tied, is here called into play—a function immediately related to accurate recognition of signal flags and lights. A daylight and binocular test, it carries the advantages of the Holmgren approach to average conditions of color viewing, with no call for manipulation of

unfamiliar apparatus or squinting into an eyepiece, and a considerable range of colors. An 8″×8″ box with four compartments, and four small apertures in the cover, labelled R, G, B, and Y, with a container of colored beads of different chromas and sizes and tweezers to lift them is used (see Stoelting) (*27*). The test is independent of the Edridge-Green 7-type theory (*33*). It runs afoul, however, of a perennial difficulty in color-sorting tests, due to the presence in the hue continuum of intermediate or "mixed" colors—orange, blue-green, purple. Shall these be tossed into the red or yellow, the blue or green, red or blue compartments? If the former is the subject to be classed as red-weak, or color-blind? Hesitations are supposed to indicate color weakness, but they may proceed from excessive conscientiousness or temperamental indecision. Further, the writer's experience with a 60-card free hue-sorting test proves that with normals as well as deviates identification of fawns and browns with oranges or yellows is not a matter of direct observation, but of specific training in the contour lines of the color solid. "Yellow," to the uninitiated, is luminosity-plus-hue. (This perhaps explains the conviction of many a red-green blind that these hues are not lacking in his color system—the quality fawn or tan acting as surrogate for green, golden brown for red.)

Nevertheless, this test has been found to be a useful auxiliary one, e.g., by Houston and others. The smallest beads test central scotoma, and a scoterythrous trend may be detected with the dark reds and magentas. Number and color of beads, and sizes should be standardized, box painted gray or white, and distribution curves for time and errors furnished.

Philip's card-sorting by color mass described earlier belongs here, though its sphere of usefulness is probably with the differential and industrial rather than mass screening tests.

II. Matching Tests. Nagel Anomaloscope

Matching by mixture (borrowed from theoretical researches) falls here, utilizing either rotating disks, the Helmholtz color-mixture spectroscope, or the instrument devised by Nagel, himself anomalous-visioned (*34*). The Rayleigh equation used to separate so-called protanomalous from deuteranomalous turns on the proportions of red light to be added to green to match yellow. Color-blind accept a wide range of ratios, color-weak and normal a narrower. The results are equivocal, however, failing to show whether the subject is green-sensitive or red-insensitive according to Houstoun and Hess (see Hayes (*3*), p. 554 f.). For you are working with three unknowns, the yellow valences of sodium, thallium, and lithium light. The variability of sensitivity to the latter in red-green blinds and in normals or color-weaks is evidenced by Pitt's luminosity curves for 11 protanopes (*35*), and Houstoun's curves for scoterythrous vision based on an unselected group of 600 (*36*). The test is time-consuming, unless cut-and-dried equations are used—in which case, Houstoun pithily remarks, if there are only three hat-sizes, there will be found only three sized heads.

A more satisfactory method is to leave green out of the equation and concentrate on variability in scoterythrous vision (alias "protanopic" and "protanomalous"), i.e., the visibility of long-wave stimuli (see threshold tests). Houstoun believes sensitivity to red may vary as 1 to 20. Canvas of astronomers and spectroscopists indicates wide differences in the emission lines visible between 680 and 800 mμ and beyond.

Since red is of high signal value, cut-off of its chromatic and luminosity functions in normal or anomalous as well as in red-green blind, is a critical matter. So far it has proven the main stumbling block in test construction, in part because of its variability, in part because of false analogies with green insensitivity (which is primarily chromatic). Actually, scoterythrous vision appears to overlie red-green blindness or weakness as astigmatism may overlie myopia or hypermetropia. Though its retinal correlates are unknown, it carries a shift of the maximal brightness region from yellow-green toward blue-green, similar to the shift in twilight or night vision (hence it may be found related to a trend toward rod vision and a preponderance of rhodopsin, the absorption coefficient of which for long wavelengths is virtually nil). Therefore, a test for the relative luminosity of blue-green *versus* yellow-green forms a second substitute for the equivocal Rayleigh equation. A third significant type of equation using disk mixture or overlapping filters

turns on the amount of blue that must be added to red or green to match gray (the equivalent of a B+Y mixture in cases of deficiency). The "protanope" (scoterythrous) requires a small though variable amount of B, his neutral strip falling on carmine to scarlet; the "deuteranope" (average red-green blind), considerably more to neutralize the yellow valence of red stimuli, his neutral line falling on an off-spectrum purplish red. For other useful equations, see M. Collins (*6*, 95 f.) and D. B. Judd (*17*).

These, however, with the exception of the threshold tests, are primarily theoretical and exploratory, unsuited to mass screening, though simplified differential tests using Munsell papers might be evolved to represent them (*37*).

Paired Matching

Matching of a set of 50 Bradley papers exposed simultaneously in order, with 5 chroma variants for each of the ten hue series, has been used effectively by Collins on her ten widely differing color deviates. A numerical rating based on results would apparently parallel degrees of ability closely. The Inter-Society Color Council is developing an aptitude test similar in type for normals, with 40 (or fewer) glossy chips representing low chroma variants of R or pR; arranged in a fixed but haphazard order. Immediate removal of the chip matched increases the difficulty of matching. The writer is using 6 paired sets of Munsell papers, B, R, G and BG chromas, and R and G hue strips in middle values, with grays and confusion colors interspersed, in the study of borderline and red-green blind cases. Except with very low chromas, however, color deviates may match successfully by means of the blue and yellow valences of their spectra, identities remaining identities. Confusion colors must be very carefully selected in varied brightnesses to trap them. For many normals, the judgment of equality, especially in surface colors, is the most difficult, slight differences in reflectance proving disturbing. Choice of match may be facilitated by mechanical devices for bringing the test color and match together at the same point of illumination (Helmbold, Balinkin). For the effect of color temperature of illumination, and of macular pigmentation on matches see Garner, Nickerson, and Judd (*38*); also Wölfflin (in Haupt, 551). This was observed as early as 1794 by John Dalton.

III. Naming Tests. Edridge-Green Lantern

Lantern tests are preferred by seamen as more cognate to their daily tasks than wool sorting. Where ability to identify and discriminate signals is in question, the usual objection to stress on naming becomes invalid. Colored filters matching signal lights and revolving disks carrying apertures of grades sizes and reducing filters with slides simulating fog and rain are provided. Forty or more combinations form the original test. Simpler lanterns (using three colors only, R, G, and Y) and shorter methods have been devised, some exposing lights singly, others in pairs at equated intensities (*39*). The latter arrangement, however, is obviously inadequate. Red and green at equated intensities are still distinguishable as different chromas of yellow, whereas under certain atmospheric conditions chromas may be equated leaving the color-blind or color-weak at a loss to identify the hue. Equation of intensities for the normal eye, moreover, may not hold for the scoterythrous. If the bluish green of our street traffic lights (which is nearly colorless for red-green blinds) is used instead of yellowish green, some of these objections cancel out. It is doubtful, however, whether reductions of the visual angle at a fixed distance (usually ten feet) may do duty for increased distance. Even a slight myopia or hypermetropia appears to affect the thresholds for red and blue (one favoring red, the other blue).

A naming test applied to two normals and two deviates by the writer, using saturated and desaturated hues in Munsell papers, showed, as expected, a tendency in the latter to swing low chroma yellows toward R or G in apparently haphazard fashion (*40*). In general, deviates can use color terms with nearly 50 percent accuracy, having acquired them by arbitrary association, as an American might pick up Arabic phrases.

IV. Discrimination and Sensitivity Tests

(*A*) *Number of discriminable hues: Houstoun's contouring method.*—Using color filters with varying degrees of overlap, Houstoun has deter-

mined the total number of discriminable hues on the periphery of the Maxwell color triangle for a number of cases (range 9–140). Confusion of saturation with hue differences—a perennial source of error—may explain his failure to locate a true dichromat (*41*). This method, which is time-consuming, belongs rather in the exploratory or supplementary category for doubtful cases. MacAdam's procedure for normals rates similarly (*42*).

(*B*) *Hue recognition: Nagel cards.*—This 16-card set, used in the German army, has gone through many editions. Each 2-1/4″ card carries a 1-3/4″ circle made up of 24 color dots (1/8″) on white. Carmine in 2 or 3 chromas, green, gray in 3 values, and in the 11th edition (1926) orange, olive, violet, and blue are used, one hue or two to a card. The twelve cards of section A are exposed simultaneously with the queries: "Which card contains red spots? Which all red? All green? All gray?" Section B (4 cards) uses scarlet, green, olive, fawn, brown, and gray spots, and is used both for naming, and for the color contrast effect (of juxtaposed spots) said to characterize color-weak or anomalous (to which group Nagel belonged). This has been used by M. Collins, Philip, Jennings, and others, but is generally held unsatisfactory, passing many color-weak (*43*). The array of 12 cards presents too complex a field for lower levels of mentality and requires too concentrated attention and too much time. Printed on gray, in five chromas, with exposure of one card at a time, however, the scheme could be adapted to sifting out three levels of sensitivity. It permits of numerical scoring.

(*C*) *Chroma thresholds and field limits.*—Chromatic sensitivity tests in several regions of the spectrum are fundamental and indispensable in prognostic, vocational, or in routine screening work, since higher thresholds (in graded series, bridging the gap from normal to abnormal) probably mark congenital as well as acquired cases. Dutch and English workers, Donders and Edridge-Green, as early as the 1870's used increased distance and diminished area, especially in their lanterns, with graded apertures and reducing filters set in revolving disks, to measure threshold sensitivity (Haupt, 244). Small rectangular spectroscopic fields and Wratten filter light boxes, with intensities regulated by Aubert diaphragm or reducing wedges, obviate the errors introduced by the older methods with their variable visual angles subtending dissimilar retinal areas; and their involvement with chromatic aberration and lens adjustment factors affecting red and blue sensitivity. These improvements can be utilized with daylight as well as unillumined surround, as both Abney and Hess have shown.

Among the pigmented surface threshold tests of the 1880's are Ole Bull's chromatometric plates and Kolbe's *Farbenmesser*, a rotating cone yielding 100 saturations (see Hayes and Haupt). These are unknown in America, but substitutes are possible with the lower chromas of the Munsell papers on matching gray, and ground glass reducing covers. A large rotating disk of full chroma, combined with an adjustable equal-value gray disk with logarithmically cut-out sector provides rings of graduated chroma shading into gray. The writer's paired Munsell chroma sets with gray jokers also locates the chroma limens roughly.

Ophthalmologists, pathologists, and others have developed perimetry as earlier stated, Engelking and Eckstein (1920) issuing papers in invariable peripherally equated hues (R, B, G, and Y) for use. So far, however, no normal distribution curves for the fields under standardized conditions appear to be available for comparison with deviates.

(*D*) *After-images.*—These have been used from the first as supplementary evidence of dichromatic vision, either through free description, matching along a scale of colors, or projection of the negative after-images of two hues exposed side by side (such as blue and violet, or red and yellow) on a gray ground. In the latter case, the two images from each pair are indistinguishable, yellowish in the first case, blue in the second, thus corroborating the reduction of the deviate's color system to two hues. Owing to the variability of the after-image, not only with the visual system of the subject, but with illumination and projection field, it is doubtful if any more precise diagnostic use could be made of it, though shortened duration is significant in color weakness according to Guttmann, and indications of an extreme scoterythrous trend should also be obvious (see M. Collins).

Wiltberger Color Test. P. B. Wiltberger, medical examiner in Civil Aeronautics, in 1939–41 produced a six item test designed to replace the Ishihara which he dubs a "pastel test." A 1″×3″ saturated glossy color rectangle selected from Klincksieck and Valette's color chip series (Paris, 1908) is exposed horizontally on one page of the booklet, three vertical chips on the page opposite. Directions are to fixate the horizontal chip for 20 seconds or more, then shift to the right-hand page, allowing the after-image to form a cross with the rectangle it matches. The series includes: (1) R (toward a carmine) with choice of Brown, Green, and White matches; (2) Y (pale) with choice of B, G (dull olive), and white; (3) G, with bP, white, and dark gray; (4) RP with B (dull), G, and white; (5) R and G, with fixation midway between, and outlines for projection below (with reversal of color scheme in after-image); and (6) a G strip in three chromas or brightnesses. All mounts are on middle gray boards (*44*).

The references supplied are inaccessible, hence it is unknown whether standardization has been attempted. At first glance, the test would seem to rest on the three obsolete Helmholtzian categories, R-blindness, G-blindness, V-blindness, with the assumption that color is completely blacked out in case of deficiency (hence the provision of white matches). It is possible it might be used to ascertain *normality*, though there is no exact complementary (under daylight illumination) among the three choices for R, Y, or RP for average vision. Its use in selecting the "color-unsafe" remains problematic, in view of the known variability of chromatic function.

(*E*) *Color contrast.*—Immediate induction of the complementary color on a contiguous gray. Use of colored shadows was made by Stilling, with light from two sources, one colored (*10*). Cohn used the optician's open E's in various sizes and positions in gray on a purple ground. Witmer's gray pendulum on a colored ground (R, G, B, or Y) with white tissue cover picks the dichromate, but some R-G weak do better than the normal, otherwise R and G grounds in three chromas might serve to detect degrees of insensitivity. A case of raised thresholds through probable nicotine poisoning has been isolated in a classroom test with the Witmer and related figures.

(*F*) *Pattern perception. "Vanishing pattern" test.*—Stilling's pseudo-isochromatic charts. This device, based upon experimental determinations of "confusion colors" for different types of deficiency, marked the first advance over the crude Holmgren wool test with its artificial categories of defect. As first issued by Dr. J. Stilling of Strasbourg (*Pseudo-isochromatische Tafeln für die Prüfung des Farbensinnes*, 1876), it was based on Hering's four primaries, and comprised ten large plates, with four examples on each. Each plate was worked out in a pair of confusion colors identical in hue for a given type of defect, selected by matches on the rotating disk made by a red-green blind painter and a blue-yellow blind teacher. A digit made up of blotches of one confusion color in several shades (to allow for slight variations in the luminosity function in deviates) on a field made up of blotches of the corresponding interchangeable color, also in several tones and values is printed on a white ground.

In the third edition (1889), differently colored plates provide for the testing of four types of deficiency: R-G blindness, R-G weakness, B-Y blindness, and shortening of the spectrum—as well as total color-blindness. Reliance is mainly on dull tones of yellows (fawns and browns) for the field color. The digits become invisible to color deviates (in many plates) through fading out of the reddish or greenish tone from oranges and olive greens, leaving low chroma yellows indistinguishable from the ground. There is a special set of plates serving to detect simulation of deficiency; another, pretense of normal vision. Excellent directions accompany this early edition. Pigments were carefully selected by Stilling (*45*).

In later editions gotten out by Dr. Hertel of Leipzig since Stilling's death in 1918, there is greater variety of colors, in higher chromas, but the directions are obscure, badly translated, and usually ignored. The distance (one meter) is rarely maintained, projecting the test digit on a different retinal area from that for which it was designed (probably macular). Odd-shaped German digits, and curious capital H's and L's render this test difficult for the average American.

Scoring. Since different groups of plates in all

the editions are designed to become invisible or visible in different types of defect (and there are fewer plates for the scoterythrous) totaling plates correct or errors (without careful adjustments) is like adding together the patient's pulse, temperature, weight, and red-corpuscle count, and diagnosing his complaint by the sum total. On the first three plates of the 17th edition it is the pattern of response that tells, $--+$ signifying ordinary R-G blindness, $++-$, scoterythrous (or protanopic) vision. Many examiners have failed to grasp this point (*46*). Novel features in the 19th and 20th editions (1937 and 1940) are plates for determining the limen for green, or for detecting heightened contrast (gray on R and G fields). Other plates use some of the devices introduced by Ishihara. Slight errors in reading a digit, such as mistaking a 3 for an 8, etc., if uncorrected on repetition at the close of the test, are accepted as an indication of color weakness; though the ingrained perceptual trend toward completing a broken arc or circle renders responses to 3's and 6's equivocal.

Since the early 1920's the most popular form of pseudo-isochromatic charts has been the Japanese set devised by Dr. Shinobu Ishihara of Tokio, especially the fifth edition with 16 plates. Clark at Johns Hopkins appears to have been its first sponsor in this country (1926). Novelties are three charts for *illiterates*, with reversible patterns for normal and deficient; two dichotomous plates, separating extreme "protanopia" from extreme "deuteranopia" through the visibility or invisibility of the red or red-purple digit of a double number; convertible digits; plates with "hidden numbers" designed for visibility only to the red-green weak or red-green blind. Ishihara's digits are *per se* more legible; and totalling the number correct less futile than in the Stilling. But the directions are inadequate, the "hidden" digit keyed apparently to Japanese eyes, as also the blue and green digit picked by Clark as a sensitive instrument, but often read incorrectly by normals. Copyrighting has proved impossible, hence the plates have been duplicated along with an easily memorized key by cheap color processes in the tabloid press, and exposed in public places, reducing the fifth edition to a parlor game (*47*). Most examiners refuse to bother to present the plates in variable order to foil cheating.

In 1939 an eighth edition with 32 plates appeared, using more 2-digit numbers, equating the plates in one color group with another more nearly by balance of angular and curvilinear digits. The colors in the hidden digits have also been altered, either by design or due to pigment difficulties rising out of war conditions, so also the first two convertible number plates. The further request from America for a digit intermediate between the two reds (R and pR) of the protanopic-deuteranopic plate was, however, ineffective. (The device of alternate readings for normal and deficient was used as early as 1916 by Podesta in his lettered wall charts.)

In spite of its shortcomings, the Ishihara, like the Stilling, has proved useful to many investigators. It served Terman in 1928 to select 50 "color-blinds" for her color classification test tryout; Downey in her study of three generations of color-blinds (though the struggle to warp her cases into the "classical typologies" of the Ishihara introduction nearly ruined the record) (*48*). Miles used it in his study of a hundred cases among Stanford students, his discovery of 27 among 375 drygoods salesmen, and his monocular examinations (*49*); Planta in his examination of 2000 Swiss schoolboys in 1932; Collins in 1937 in her study by a battery of tests of 360 applicants for apprenticeship in color printing; Murray in a study in naming of saturated and desaturated colors (1933), a tryout of a new group hue classification test on 55 high school art class and college students, and 75 eighth to tenth grade pupils (1935), in 1936 in classification of the responses of 228 color deviates among 3130 students examined by Cornell University. At first few realized that the test was throwing down color-weak along with color-blind—and that total scores might not run parallel to degrees of defect.

The usefulness of a rapid-fire test of this order to cut out cases for further examination is undeniable (whether all who fail are deviates, all who pass, normals, is another matter). Attempts to adapt the charts for group testing through lantern slide reproductions were early made, but proved unreliable.

In this country the Beck Engraving Company produced and the American Optical Company published, at the request of the Services, a se-

lected number of Ishihara and Stilling plates in 1940, copyrighting their copy. No information is available as to whether deviations from the original are deliberate or accidental, or whether the edition has been standardized by mass testing and tabulation of results.

Pseudo-isochromatic tests all possess certain undoubted advantages. They are speedy, they virtually dispense with the need of instructions, they combine field measures with test of a central area, constituting in a fashion a substitute for perimetry. They hold attention by their interest and variety, requiring only short pulses of concentration. They are empirical, based on actual measurements, and possess greater flexibility than most cut-and-dried schemes, owing to their mosaic structure and use of varied chromas, brightnesses, and sizes of dots. They presuppose, of course, correction for defects of refraction.

Objections to the Japanese and German plates are based in part on the suspicion that certain plates are keyed to visual systems unlike ours, primarily on the use of digit patterns. Digits are unequatable in difficulty and easily memorizable, the task of withholding the keys from the public virtually insuperable. Geometric figures which can be orientated in any direction have been introduced to meet this difficulty. Examples are Jensen's use of the clock hand (1936), Schaaff's mosaic diagrams using Landolt's broken circle (1925); Rabkin's polychromatic charts using triangles and circles along with digits, which appeared first in 1936 (*50*). The latter, a Russian output, is highly recommended by a number of examiners, including M. Collins. The directions are excellent. Of the 20 plates, 10 are for general diagnosis, 8 for differential, allowing rating by degree and kind of defect as in the early Stilling. During the last five war years, it should be added, the printing of most foreign tests has deteriorated. While the pigments are fairly permanent if not exposed, there apparently has been less careful scrutiny and discarding of imperfect imprints.

V. Serial Arrangements of Hues and Chromas Hue Classification

Tests implying ability to analyze the integral color experience into three aspects are relatively recent psychological developments. In 1926, C. S. Myers introduced chroma series in R, Y, and B in an industrial test in England (as described earlier). About the same date, Murray began utilizing serial hue arrangement with or without interpolated grays or complementaries to locate critical areas in color-weak and borderline cases. A 20-hue circle test on a white ground was developed, with 1-inch disks of Munsell paper equated in chroma and brightness (at the 4/4 levels). This was abandoned because the hue steps were not fine enough and because trained R-G deficients could make practically perfect scores by arranging the samples as chromas of yellow and of blue, while untrained normals, unfamiliar with the nuances of the continuum, might be nonplussed. Critical segments of the Munsell 100-hue circle (8–10 in a set), mounted on gray, are now being used. Farnsworth's test to be reported later in this journal uses 85 of the 100 hues in small disks mounted in protective black caps and divided into four sets. Regions of marked error in arrangement occur, not singly, but in pairs on opposite sides of the circle in the regions at 90° from the neutral bands in R-G and B-Y deficiency. By starting with a pilot cap or two and instructing the subject to proceed by finding the nearest match at each step, the handicap of unfamiliarity with the continuum concept is minimized. The test promises to isolate cases of B-Y (or V-YG) blindness more readily than do the pseudo-isochromatic plates devised for this purpose.

The hue classification tests described earlier (under group testing) properly fall under this caption since they imply familiarity with the various dimensions of a color, and ability to group together the various members of each hue family, e.g., the tints, shades, and chromas of yellow (Terman, Murray).

VI. Reproduction of a Color Pattern

The Roaf painting test was used by Collins in the Edinburgh laboratory in her analytical study of ten color deviates. A geometrical design in 10–20 colored segments is set for copy. A simplified design with 10 numbered divisions is used by Murray, reproduced with the aid of a set of Prang's crayons (24 in number). Typical results

for a red-green blind art student with a slight scoterythrous trend show G replaced with light brown, R with B, O with reddish brown, V with B, GY with G, B-G with gray: score, 40 percent correct. By this method a rough idea of the confusion colors of the different types may be obtained, though chance and the fact that identities are still identities for the deviate obscure the results.

E. SUMMARY AND RECOMMENDATIONS

Fifteen years' experience with a wide diversity of cases and an extended survey of the literature indicate that:

(1) Mass investigations of aberrant and normal-visioned must prelude any marked advance in color vision testing. Spectrally homogeneous light, and the solar, not the equal energy spectrum, will prove most reliable and helpful.

(2) Obsolete and purely theoretical terms and constructions should be abandoned. Whether retinal research will finally disclose a tri- or tetrapartite chromatic mechanism is not yet clear, but since trichromatic formulations of the test problem have so far failed to meet practical needs, tetrachromatic deserve wider trial. The latter have the additional merit of permitting the observed facts to be easily diagrammed and explained. Recent visual research summarized in the Chicago Symposium on *Visual Mechanisms* indicates, moreover, that search for explanations might profitably be transferred from hypothetical photochemical substances in the cones to photoelectric processes in the bipolar layers of the retina. Rhodopsin and porphyropsin may act merely as sensitizers in night and daylight vision, respectively. Theorists should further take account of the fact that scoterythrous vision (termed protanopic by the followers of von Kries and Nagel) resembles closely a trend toward twilight vision. Chromatic variations should therefore be checked against dark adaptation curves.

(3) Past experience with pirated printing and cheap reproductions indicates that there should be two distinct sets of tests: one, devised, standardized, copyrighted and controlled by the United States Government in consultation with scientists for military use; a second set, commercialized for use in schools and industry. Both sets should include screening tests, and differential tests with quantitative scores adapted to specific ends, fitted to jobs or vocations. Frequency tables of responses for each item should accompany instructions. Scoring should permit the assignment of either quartile or quintile rank in the population or a given group.

(4) No individual should be diagnosed as color-blind on a single test, or by anyone but an expert with extended training. At least three different tests are requisite. The human eye is more complex than any spectrophotometer yet invented, and the ways in which it may deviate from perfect operation more numerous. No single device would suffice to diagnose myopia, astigmatism, aphoria, and aniseikonia. The same holds true for deviations in color vision.

(5) The ideal screening test (or battery of tests) should not only identify the normal-visioned; it should if possible single out the totally color-blind (*51*), the R-G blind, and the R-G weak, the B-Y blind and B-Y weak (less numerous classes). Finally, normals and deviates alike should be examined with a projected spectrum or with small spectrometer fields in both the long-wave and the short-wave end of the spectrum—i.e., in the red and in the violet, to determine possible trends toward scoterythrous ("protanopic") or scotocyanic ("tritanopic") vision. Differential tests should chart threshold sensitivity and discrimination at at least six critical points on the hue continuum.

(6) Lastly, school children should be tested at all ages in order to determine what proportion of the 8 to 10 percent of adult defect is congenital, how much acquired; in order to secure also a sounder basis for generalizations on heredity, and the application of remedial measures (*52*).

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Minutes of the Twenty-First Meeting of the Board of Directors of the Optical Society of America, Incorporated

NEW YORK, NEW YORK, MARCH 4, 1943

IN addition to the transaction of routine business and the receiving of reports of committees, the following items of general interest to members of the Society were taken up.

Announcements by Secretary

Results of letter ballots:

1. Approval of resolution to hold winter meeting of Society in New York City on March 5 and 6, 1943.
2. Approval of appointment of Victor Chalupski and Walter Granville as additional members of the Program Committee for the winter meeting, 1943.
3. Approval of the nomination of R. C. Gibbs to succeed himself as OSA representative on the Governing Board of the A.I.P. for a term to expire in February, 1946.

Announcement of Appointments by President

1. Proxies for the Optical Society at the annual meeting of the American Institute of Physics on February 27, 1943:
   LeGrand H. Hardy Selig Hecht

Report of the Ives Medal Committee

On recommendation of the Committee for the Award of the Frederic Ives Medal in 1943, the Board voted unanimously to award the Frederic Ives Medal to Dr. L. A. Jones of the Eastman Kodak Company. It was expected that the Medal will be bestowed at the annual meeting of the Society in October.

Annual Meeting of Society

It was voted to hold the next annual meeting in Pittsburgh during the early part of October. The nomination of G. W. Moffitt to be Chairman of the Program Committee for this meeting was confirmed; other members of the Committee to be appointed later.

On the recommendation of G. R. Harrison, the action taken last October relative to a summer meeting in 1943 was rescinded. Dean Harrison reported that, although there was expectation of a good attendance and an adequate supply of contributed papers, the wartime activities at M.I.T. made the holding of the usual type of summer meeting impossible. It was felt by the Board of Directors that, in view of this circumstance, special provision should be made at the annual meeting for the inclusion of a program of papers on applied spectroscopy.

ARTHUR C. HARDY, *Secretary*

Report of the Editor of Publications

Statement of Operations of the Journal of the Optical Society of America for the Year Ending December 31, 1942

Income

Non-Member Subscriptions		$4,780.85
Net Income from Published Articles		1,592.56
Net Income, Cumulative Index		16.87
Net Income from Sale of Back Numbers		450.38
Total Income Exclusive of Member Subscriptions		$ 6,840.66

Expense

Printing and Mailing			$8,291.13
Engraving			1,553.02
Editorial Mechanics:			
Salaries	$1,085.39		
Office Expense	245.17	1,330.56	
Subscription Expense:			
Salaries	$1,160.44		
Office Expense	258.44	1,418.88	
Other Expenses:			
Auditing, Insurance, and Miscellaneous		339.37	
Editorial Office (Cambridge):			
Salaries	$1,000.00		
Expense	119.41	1,119.41	
Total Cost of Editing and Publishing Journal			$14,052.37
Net Cost of Operating Journal and Furnishing It to Members			7,211.71

Number of Pages Published	*1942*	*1941*	*1940*	*1939*
Text and Index	758	774	666	550
Covers and Front Material	72	72	72	72
Total	830	846	738	622

(Signed) G. R. Harrison, *Editor*

Annual Report of the Treasurer of the Optical Society of America for the Fiscal Year 1942

CASH TRANSACTIONS JANUARY 1, 1942 TO DECEMBER 31, 1942

Receipts

Dues	$3,875.04	
Dues in advance	3,836.55	
Interest on unallocated securities	973.98	
Interest on Ives Medal Fund Bonds	16.25	
Interest on A. Lomb Fund Bonds	50.00	
Contributions	7,000.00	
		$15,751.82

Disbursements

Journal Publication Expense	$7,027.94	
Journal Editorial Expense	1,125.00	
President's Expense	10.58	
Secretary's Expense	1,284.56	
Secretary's Travel Expense	59.23	
Treasurer's Expense	381.71	
Membership Committee Expense	17.55	
Local Committee Expense	39.68	
Adolph Lomb Fund Expense	20.51	
Specially Appropriated Expenditures		
Inter-Society Color Council Dues	25.00	
U. S. Nat. Comm. of Int. Comm. on Ill.	33.00	
Bonds for A. Lomb Memorial Fund	296.46	
		$10,321.22

Excess of receipts over disbursements		$ 5,430.60
Balances—December 31, 1941		
Unallocated cash in banks	$1,423.27	
Ives Medal Fund interest	108.49	
A. Lomb Fund interest	227.91	
Local Committee Fund	177.96	1,937.63
Cash balance, December 31, 1942		$ 7,368.23

Statement of 1942 Operations

Income

Dues	$7,668.24
Investments	1,040.23
	$8,708.47*

Expenses

Journal Publication	$ 6,092.30
Editorial Expense	1,000.00
President's Expense	10.58
Secretary's Expense	1,078.06
Secretary's Travel Expense	59.23
Treasurer's Expense	381.71
Colorimetry Committee	0.00
Membership Committee	17.55
Photographic Standards Committee	0.00
Program Committee	0.00
Contingencies	0.00
Contributions to the support of other Organizations:—	
A. I. P. 15%	2,189.44
I. S. C. C.	25.00
U. S. Committee I. C. I.	33.00
	$10,886.87
	8,708.47
Deficit	$ 2,178.40

* This does not include the sum of $7,000.00 obtained by contributions, which have been applied against the accumulated operating deficits of the last few years. The contributors are:

American Optical Company	—$2,000
Bausch & Lomb Optical Company	— 2,000
Eastman Kodak Company	— 2,000
General Electric Company	— 500
Keuffel & Esser Company	— 500

Ives Medal Fund

Income

Principal sum	$ 500.00	
Cash interest balance, Jan. 1, 1942	108.49	
Bond interest accrued during 1942	16.25	
		$ 624.75

Disbursements

None	00.00	00.00
Balance, December 31, 1942		$ 624.75

Note: The principal sum of $500.00 is invested in the U. S. Treasury 3¼ percent 1945 certificates. They are included in the bonds reported in the accompanying Investment Statement.

Adolph Lomb Memorial Fund

Income		
Principal sum	$2,000.00	
Cash interest balance Jan. 1, 1942	0.00	
Bond interest accrued during 1942	50.00	
		$2,050.00
Disbursements		
For medal for James G. Baker	20.51	20.51
Balance, December 31, 1942		$2,029.49

Note: The principal sum of $2,000 is invested in U. S. 2½ percent Treasury Bonds of 1972. They are included in the bonds reported in the accompanying Investment Statement.

Local Committee Fund

Income	
Cash balance, January 1, 1942	$ 177.96
Disbursements	
Expenses connected with 1942 meeting	39.68
Balance, December 31, 1942	$ 138.28

Investments

Our trust officer reports our holdings as of December 31, 1942 as follows:

	Book Value	Market Value	1942 Income	Rate Against Book Value
Bonds				
Interest Balance			$ 74.90	
$7,000 Atchison, Topeka & Santa Fe 4% Mortgage Bonds 4–11–33	$ 7,000.00	$ 7,822.50	280.00	4%
$5,600 U.S.A. 3¼% Treasury Bonds	5,625.67	5,712.00	182.00	3.23%
$10,000 U.S.A. 2½% Treasury Bonds	10,001.31	10,078.00	225.83	2.5 %
Total Bonds	$22,626.98	$23,612.50	$ 762.73	3.15%
Stocks				
10 Shares Eastman Kodak Common	$ 1,718.19	$ 1,495.00	$ 67.50	3.93%
65 Shares General Electric Common	2,544.23	1,998.75	105.00	3.58%
35 Shares Kennecott Copper Corp. Common	1,729.53	915.00	105.00	6.07%
Total Stocks	$ 5,991.95	$ 4,408.75	$ 277.50	4.4 %
Total Investments	$28,618.93	$28,021.25	$1,040.23	3.41%

Note: The $74.90 listed as interest balance represents the difference between $113.33 accumulated interest received at the time of the sale of $8,000 of 3 percent U. S. Treasury Bonds on December 5, 1941 and the accumulated interest amounting to $38.43 paid in purchasing $10,000 of 2½ percent 1972 U. S. Treasury Bonds on December 15, 1941. Of this amount $24.17 can be credited as income from the 2½ percent U. S. Treasury Bonds to bring it up to $250.

Included in the above are $2,000 of U. S. Treasury 2½ percent 1972 Bonds which are the property of the Adolph Lomb Memorial Fund and $500 of U. S. Treasury 3¼ percent 1945 Bonds, the property of the Ives Medal Fund.

The undersigned, having been duly appointed to audit the books of the Treasurer of the Optical Society of America, Inc., from January 1, 1942 to December 31, 1942, hereby certify that the Treasurer's report of receipts and disbursements is correct as shown by records, vouchers, bank statement, etc., and that his accounts check accurately with vouchers and bank statements.

(Signed) Carl L. Bausch, Fred H. Perrin, *Auditors*

Annual Report of the Secretary of the Optical Society of America, for the Calendar Year 1942

Membership Record

January 1, 1942 to January 1, 1943

	Honorary	Regular Annual Payment	Regular Life Payment	Associate Individual Annual Payment	Associate Corporation	Emeritus	Student	Total
Membership as of record in the books of the Secretary 1–1–42	4	463	6	534	15	13	9	1044
Gains during 1942								
By election as of 1–1–42	0	0	0	128	4	0	10	142
By election as of 1–1–43	0	0	0	102	0	0	7	109
By reinstatement as of 1–1–40	0	1	0	0	0	0	0	1
By reinstatement as of 1–1–41	0	0	0	1	0	0	0	1
By reinstatement as of 1–1–42	0	3	0	3	0	0	1	7
By reinstatement as of 1–1–43	0	2	0	3	0	1	0	6
By transfer 10–29–42 as of 1–1–43	0	60	0	0	0	0	0	60
By transfer from student to associate membership as of 1–1–43	0	0	0	3	0	0	0	3
Losses during 1942								
By death	0	5	0	4	0	0	0	9
By resignation as of 1–1–42	0	5	0	8	0	0	0	13
By resignation as of 12–31–42	0	13	0	12	0	0	0	25
By transfer 10–29–42 as of 1–1–43	0	0	0	60	0	0	0	60
By transfer from student to associate membership as of 1–1–43	0	0	0	0	0	0	3	3
By expiration of membership	0	0	0	0	0	0	8	8
By separation for non-payment as of 1–1–42	0	5	0	7	0	0	0	12
Membership as of 1–1–43	4	501	6	683	19	14	16	1243

Elected during 1942 as of January 1, 1942

Ainsworth, George (1740 A)
American Cystoscope Makers, Inc. (1684 AC)
Anslow, Gladys Amelia (1719 A)
Balamuth, Lewis (1758 A)
Ballard, James W. (1717 A)
Barnett, C. E. (1685 A)
Barr, Joseph D. (1779 A)
Bastien, Roy Charles (1709 A)
Bowen, E. Clinton (1679 A)
Brooks, Charles Lutz (1759 A)
Brown, Fordyce M. (1846 A)
Bryant, Carroll W. (1714 A)
Bryant, W. M. D. (1663 A)
Burgener, John E. (1769 A)
Byers, Robert C. (1715 A)
Centeno, Melchor, V. (1725 A)
Chapman, Robert M. (1741 A)
Clapper, Franklin R. (1792 S)
Cline, James E. (1702 A)
Cohen, Norman F. (1720 A)
Constantin, Monego J. (1760 A)
Creitz, Ellis E. (1686 A)
Dollmann, Elsie M. (1829 A)
Douden, William L. (1698 A)
Douglas, Charles A. (1687 A)
Dreyfuss, R. M. (1738 A)
Dunderman, Frank V. (1683 S)
Dunn, E. J., Jr. (1688 A)
Dunn, Edward J. (1778 A)
DuPont de Nemours & Co., E. I. (1724 AC)
Eberly, Robert E. (1752 A)
Ewing, Dwight T. (1727 A)
Farnsworth, Dean (1732 A)
Fish-Schurman Corporation (1757 AC)
Fisher, Harold M. (1853 A)
France, Walter D. (1664 A)
Freeman, Gerald O. (1699 A)
French, Hobert W., Jr. (1830 A)
Friedman, Harry S. (1674 A)
Gard, Orin P. (1669 A)
Gibb, Thomas R. P. (1706 A)
Grace, Frank E. (1780 A)
Graham, Robert C. (1873 A)

Elected during 1942 as of January 1, 1942 (continued)

Grosch, Herbert R. J. (1681 A)
Harrington, Roger E. (1796 A)
Harrison, William Hartley (1797 A)
Hartman, Werner (1742 A)
Heijn, Paul Cornelis (1721 A)
Hellige, Peter W. (1710 S)
Herrmann, Leon C. (1736 A)
Hett, John H. (1666 A)
Hopfield, J. J. (1748 A)
Horsfall, R. Bruce, Jr. (1662 A)
Jackson, Trumbull Starr (1800 A)
Jameson, Dorothea (1744 A)
Jay, William H. E., III (1772 A)
Jones, Richard Norman (1705 A)
Judkins, Stanley L. (1739 A)
Jukkola, Waino H. (1754 A)
Karush, Fred (1737 A)
Kashdan, William H. (1761 A)
Kebler, Richard W. (1889 A)
Kerridge, Philip M., Jr. (1743 A)
Kimen, John G. (1682 A)
Kirtchik, Hyman (1718 A)
Klebba, Arthur A. (1762 A)
Knoll, Henry A. (1886 S)
Koomen, Martin (1803 A)
Lesch, Florence L. (1766 A)
Machler, Raymond Charles (1707 A)
Mack, Albert (1700 A)
May, Albert (1680 A)
McGonnagle, Warren J. (1713 A)
McNally, J. Rand, Jr. (1763 A)
Mears, Leverett B. (1722 A)
Menke, Warren W. (1689 A)
Merle, John, Jr. (1787 A)
Merrill, John B. (1701 A)
Mrozowski, Stanislaw (1836 A)
Nahstoll, George A., Jr. (1690 A)
Newman, Seymour (1862 A)
Nimeroff, Isodore (1691 A)
Nisbet, Dixon F. (1697 A)
O'Brien, Brian, Jr. (1806 S)
Orr, Leighton (1807 A)
Orser, W. Donald (1670 A)
Pajes, Wolf S. (1746 A)
Pearson, Frank Arthur (1692 A)
Perry, James Whitney (1879 A)
Pfister, Rudolf J. (1880 A)
Pickering, P. W. (1667 A)
Poehlman, William J. (1812 A)
Pomerance, Herbert S. (1730 S)
Powers, Stanley A. (1671 A)
Projector, Theodore H. (1693 A)
Read, Harry Stafford (1704 A)
Reynolds, Leon M. (1672 A)
Rolf, Frederick W. (1750 A)
Roos, Paul A. (1749 A)
Rosett, Bernard (1673 A)
Rouvina, James (1659 A)
Rudolph, Hellmuth C. (1716 A)
Ruhe, Carl (1753 A)
Ryan, Lloyd F. (1728 A)
Sachtleben, Lawrence T. (1764 A)
Schales, Otto (1708 A)
Schnable, George K. (1839 S)
Schuch, John (1703 A)
Schumacher, Brice A. (1668 A)
Serniuk, Walter (1888 A)
Sheftel, Milton S. (1648 A)
Simon, Frederick T. (1777 A)
Simpson Optical Mfg. Co. (1882 AC)
Simpson, S. F. (1765 A)
Smith, Alan A. (1711 S)
Smith, Daniel (1676 A)
Smith, H. D. (1658 A)
Smith, Howard Lambert (1694 A)
Smith, John H. (1813 A)
Spencer, Domina E. (1677 A)
Spike, J. Edward, Jr. (1665 A)
Spindel, Sidney Simon (1575 A)
Stamm, Robert Franz (1756 A)
Stearns, Edwin I. (1735 A)
Stultz, Keith F. (1695 A)
Sullivan, Harris Martin (1723 A)
Swanson, Mark W. (1773 A)
Sweany, John B. (1814 A)
Tabin, Julius (1729 S)
Taylor, Edward J. (1726 A)
Theel, Percival (1751 A)
Tralli, Nunzio (1733 A)
Urbach, Franz (1712 A)
Van Dien, J. Edward (1731 A)
Wakefield, Ernest H. (1747 A)
Weaver, W. R. (1745 A)
Weil, Herschel (1817 S)
West, Cutler D. (1661 A)
Williamson, Barbara (1867 A)
Young, Larry L. (1696 A)
Zirkind, Ralph (1678 A)
Zulon, John S. (1820 A)

Elected during 1942 as of January 1, 1943

Amann, Rudolf (1821 A)
Amdursky, Mark Ernest (1822 S)
Arnott, Edward G. F. (1844 A)
Aronson, C. J. (1823 A)
Ashe, Frank C. (1848 A)
Ball, G. Milton (1845 A)
Banning, Mary (1788 A)
Barkley, Charles G. (1781 A)
Baum, Alvin J., O.D. (1789 A)
Baum, Frederick J., Jr. (1770 A)
Baum, William (1790 S)
Beardsley, Niel F. (1847 A)
Benson, Bernard (1791 A)
Betz, Howard (1899 A)
Beyer, Karl W. (1774 A)
Bialecki, Adolph (1824 A)
Boyd, Robert A. (1825 A)
Broadwell, Samuel J. (1875 A)
Bruno, Michael H. (1896 A)
Butterfield, John V. (1826 A)
Campbell, H. N. (1775 A)
Carlson, Lee Gerald (1876 A)
Chapman, James M. (1877 A)
Coakley, W. Roger (1900 A)
Coburn, Rodney C. (1755 A)
Cohen, Joseph H. (1767 A)
Conant, Russell W. (1793 A)
Conner, Willard P. (1849 A)
Cornog, I. Clyde (1850 A)
Coulliette, James H. (1891 A)
Dakin, Ralph K. (1794 A)
Dauber, Joseph (1851 A)
DePaolis, Paul F. (1782 A)
Dianetti, Joseph (1827 S)
Downing, Joseph R. (1895 A)
Ellestad, Gerhard A. (1852 A)
Feder, Donald Perry (1795 A)
Fortmiller, Louis J. (1828 A)
Goldblatt, Alan (1901 A)
Goodwin, William J. (1771 A)
Graham, Robert E. (1854 A)
Griffiths, Victor T. (1768 A)
Hadley, Charles Wendell (1831 A)
Hamilton, Russell D. (1902 A)
Hamlin, John R. (1855 A)
Hawk, Martha L. (1903 A)
Hazeltine, Alan (1904 A)
Higgins, George C. (1783 A)
Hill, Harry (1905 A)
Holland, Thomas Edwin (1798 A)
Hudson, Lena M. (1799 A)
Huggins, Maurice L. (1784 A)
Imus, Henry Alfred (1856 A)
John, Paul (1832 A)
Johnson, Tyrroll (1801 A)
Kesel, Robert E. (1802 S)
Keselik, Joseph (1887 S)
Kinsinger, W. G. (1857 A)
Krueger, Roland F. (1878 A)
Lab, Roy F. (1833 A)
Loewenstein, Erich (1804 A)
Marshak, Robert E. (1834 A)
Martin, Robert L. (1835 S)
Miller, Rudolph (1858 A)
Montgomery, Mary Thomas (1884 A)
Muller, Robert M. (1859 A)
Mulvey, Bernard (1776 A)
Newcomb, Walter C. (1805 A)
Nichols, J. Burton (1885 A)

Elected during 1942 as of January 1, 1943 (continued)

Oughton, Charles D. (1808 A)
Paul, Henry E. (1860 A)
Pearson, Fred, Sr. (1906 A)
Peet, A. Brainard (1883 A)
Perkins, Willard T. (1809 A)
Pestrecov, Konstantin (1894 A)
Peterson, Lee (1837 A)
Pitkin, Pauline H. (1810 A)
Platt, Joseph B. (1811 A)
Polster, Harry DeLeon (1838 A)
Pride, Gilbert E. (1881 A)
Rank, David H. (1861 A)
Reiss, Max (1897 A)
Scharf, Philip T. (1785 A)
Schwartz, Charles (1840 A)
Scofield, Francis (1898 A)
Scott, Robert W. (1841 A)
Seitz, Frederick (1863 A)
Stevens, Ludlow Robert (1871 A)
Stewart, Harold S. (1842 A)
Stilwell, G. Raymond (1864 A)
Story, Robert V. (1865 A)
Tackaberry, Robert Bernard (1866 A)
Tobias, Julian M. (1872 A)
Tomkins, Frank S. (1870 A)
Turrettini, Fernand (1874 A)
Uffert, Jane M. (1893 A)
Van Zee, Arthur F. (1892 A)
Vance, E. R. (1907 A)
Vigo, Samuel (1815 A)
Wadlund, Arthur P. R. (1909 A)
Walker, Robert C. (1816 A)
Walls, Gordon Lynn (1890 A)
Wiley, S. Richard (1908 A)
Williams, Franklin C. (1786 A)
Wilson, Richard J. (1818 A)
Windle, Maurice L. (1843 A)
Witmer, Enos Eby (1868 A)
Wood, James L. (1819 S)
Woods, John T. (1869 A)

Reinstatement during 1942 as of January 1, 1940

Wilber, David T. (827 R)

Reinstatement during 1942 as of January 1, 1941

Miller, Norma Doell (1132 A)

Reinstatements during 1942 as of January 1, 1942

Bronk, Detlev (473 R)
Cottrell, Caspar L. (323 A)
Fassin, Gustave (943 R)
Filler, Aaron S. (1504 S)
Ireton, H. J. C. (875 A)
Martin, Louis C. (1113 R)
Welch, George B. (745 A)

Reinstatements during 1942 as of January 1, 1943

Ferree, Gertrude Rand (159 R)
Hopkins, Robert Earl (1091 A)
Ingalls, Arthur L. (865 A)
Ingersoll, Leonard R. (136 R)
Merritt, Ernest (275 RE)
Palmer, Roy A. (1086 A)

Elected to Regular Membership by Action of the Board of Directors, October 29, 1942, effective as of January 1, 1943

Ainsworth, George (1740 A)
Aklin, George H. (1262 A)
Anslow, Gladys Amelia (1719 A)
Balinkin, Isay A. (1070 A)
Ballard, James W. (1717 A)
Barnes, Norman F. (1186 A)
Bartley, S. Howard (1618 A)
Bellamy, Blanche R. (1215 A)
Bingham, Ronald H. (1422 A)
Bronson, S. Davis (1146 A)
Bryant, Carroll W. (1714 A)
Bubb, Frank W. (1521 A)
Centeno, Melchor, V. (1725 A)
Chalupski, Victor (1008 A)
Colton, Howard C. (1212 A)
Condit, Harold R. (1227 A)
Cooper, F. L. (490 A)
Cunningham, Frederick W. (444 A)
DePaolis, Paul F. (1782 A)
Dieke, G. H. (1634 A)
Douden, William L. (1698 A)
Driscoll, Walter G. (1582 A)
Duntley, Seibert Q. (1064 A)
Ells, Victor R. (1509 A)
Emery, Frederic H. (1303 A)
Fanter, Walter R. (1514 A)
Gardner, William A. (1243 A)
Gibb, Thomas R. P. (1706 A)
Holmes, F. M. Emerson (911 A)
Horsfall, R. Bruce, Jr. (1662 A)
Householder, F. F. (504 A)
Kavanagh, Arthur J. (1507 A)
Kerridge, Philip M., Jr. (1743 A)
Liben, William (1261 A)
Mahan, A. I. (1540 A)
Majors, Kenneth R. (1325 A)
Merrill, John B. (1701 A)
Miller, Osborn M. (954 A)
Morse, Richard S. (1252 A)
Mueller, Hans (1652 A)
Nutting, Perley G., Jr. (1142 A)
Platt, John R. (1496 A)
Potter, Rowland S. (1053 A)
Powers, Stanley A. (1671 A)
Ramsay, Bertrand P. (1461 A)
Rosett, Bernard (1673 A)
Sabine, George B. (1245 A)
Sachtleben, Lawrence T. (1764 A)
Shurcliff, William A. (1351 A)
Shurkus, Albert A. (1592 A)
Staunton, John J. J. (1654 A)
Stearns, Edwin I. (1735 A)
Steiner, Oscar (891 A)
Stevens, Paul W. (1080 A)
Sturkey, Lorenzo (1596 A)
Talbot, Samuel A. (1260 A)
Turrettini, Fernand (1874 A)
Urbain, Walter M. (1604 A)
Urbanik, John G. (1218 A)
Zinzow, William A. (1373 A)

Transferred from Student to Associate Membership as of January 1, 1943

Altman, J. H. (1641 S)
Herman, William F. (1638 S)
Kelly, Joseph B. (1639 S)

Deaths during 1942

Anthes, E. H. (951 R) (Died on August 3, 1942)
Beutler, H. (1611 A) (Died on December 17, 1942)
Ferree, C. E. (158 R) (Died on July 26, 1942)
Finn, Alfred N. (374 R) (Died on September 21, 1942)
Frederick, C. W. (7 R) (Died on November 29, 1942)
McNicholas, J. H. (1395 A) (Died on July 23, 1942)
Oltman, R. E. (1444 A) (Died on July 25, 1942)
Pfanstiehl, Carl (1122 A) (Died on February 28, 1942)
Pineo, O. W. (566 R) (Died on September 5, 1942)

Resignations during 1942 as of January 1, 1942

Detwiler, S. R. (1280 AA)
Filler, Aaron S. (1504 A)
Gamble, D. L. (950 R)
George, E. F. (204 R)
Hotaling, Elmer E. (352 R)
Kelcy, A. (1127 A)
King, B. J. (1157 A)
Mayo, Philip R. (917 A)
Myers, J. W. (554 A)
Nelson, C. N. (1231 R)
Rodden, Clement J. (1407 A)
Ryer, E. Leroy (312 R)
Stewart, Irvin (1110 A)

Resignations during 1942 as of December 31, 1942

Ashcroft, A. Griffin (1197 A)
Blanchard, Julian (34 R)
Buttolph, L. J. (360 R)
Cohen, Norman F. (1720 A)
Crabtree, John I. (908 R)
Durfee, Walter C. (1302 A)
Fairbanks, Floyd C. (299 R)
Flege, R. K. (1449 A)
French, Helen S. (1305 R)
MacLeod, Robert B. (1562 R)
Maltby, Margaret E. (781 A)
Marrison, W. A. (479 R)
McHargue, James S. (1382 AA)
Merritt, Ernest (275 R)
Middleton, W. E. Knowles (1040 R)
Mrgudich, J. N. (1546 A)
Nicholas, Warren W. (1337 A)
Palmer, Roy A. (1086 R)
Severinghaus, Willard L. (812 R)
Sheppard, Ernest (1495 A)
Sink, M. Virginia (1353 A)
Sklar, Alfred L. (1405 A)
Turrettini, Edmond (225 R)
Tuttle, Harris B. (1206 A)
Van Arsdel, W. B. (179 R)

Losses by Expiration of Membership

Forsbergh, P. W. (1622 S)
Hellige, P. W. (1710 S)
O'Brien, Brian, Jr. (1806 S)
Pomerance, H. S. (1730 S)
Sheetz, J. W. (1624 S)
Weil, H. (1817 S)
Whitmore, E. W. (1620 S)
Zeitz, Carl (1655 S)

(Signed) ARTHUR C. HARDY, *Secretary*

Proceedings of the Winter Meeting of the Optical Society of America

HOTEL PENNSYLVANIA, NEW YORK, NEW YORK, MARCH 5–6, 1943

THE winter meeting of the Optical Society of America was held in New York on March 5–6. In addition to the contributed papers, two Symposia of invited papers were featured, one on Vision, and the second, arranged by the Inter-Society Color Council, on Color-Blindness and Color-Blindness Tests.

SYMPOSIUM OF INVITED PAPERS ON VISION

A comprehensive review of the structure of the eye and the mechanism of vision was presented by the first speaker, Dr. Gordon L. Walls of the Bausch & Lomb Optical Company. This led into a discussion of visual resolution of the fovea, from the point of view of perception of pattern, perception of a bright spot in the visual field, and perception of a dark spot. The geometry of the receptors was outlined for each of these cases, and also for the resolution of parallel lines. The effect of secondary factors, such as exposure time, absorption within the eye, refractive errors, were considered.

Past and proposed methods for the measurement of binocular acuity, vernier acuity, and stereo acuity were described, and the results of recent studies were presented.

Dr. Kenneth N. Ogle of the Dartmouth Eye Institute discussed some physiological aspects of the eye as an image-forming mechanism. His paper dealt with the general problem of the size of the retinal image of an eye, the refractive error (ametropia) of which is corrected by an ophthalmic lens, and the problem of the nature of that error. Two general types of ametropia occur; axial ametropia due to change in length of the eyeball, and refractive ametropia due to changes in the dioptric elements of the eye. The size of the retinal image of the corrected ametropic eye is different according to whether the ametropia is axial or refractive in nature.

Spherical ametropia (which excludes astigmatism) has been generally regarded as axial, especially in cases of high myopia. Recent evidence points to the possibility that refractive and axial ametropia may be equally important factors. This problem was discussed from the point of view that the difference in size between the images of the two eyes measured in cases of spherical anisometropia (difference in spherical errors between the two eyes of a given individual) may provide statistical evidence for determining the nature of the ametropia. Data on a number of cases were shown which point to the conclusion that in the population sample studied, refractive ametropia is the cause, at least in part, of a large percentage of the cases of spherical anisometropia.

Dark adaptation is a phenomenon we all know by experience. Problems of dark adaptation, which have become more complex in times of war, were discussed by Charles Sheard of the Mayo Foundation. A number of factors must be considered among which are the area of the retina investigated, the size and location of the excited portion of the retina (as pointed out by Hecht), the effect of consecutive cone and rod adaptation and the intensity, duration, and color of the light used. Data for various groups, including children and aviators, were presented. The effects of vitamin deficiencies and return to normalcy of the level of threshold has received considerable attention. Equipment was described for carrying out experiments on the effect of oxygen supply on dark adaptation, and the effect of various simulated altitudes on response was shown.

The subject "Some Factors and Implications of Color Constancy" was discussed by Harry Helson of Bryn Mawr College and The Foxboro Company in the concluding paper of the symposium on Vision. Dr. Helson pointed out that the colors and forms of objects tend to remain fairly constant in spite of changes in the amount and quality of the illumination and the pattern of light rays which they send to the eyes. Thus two "white" papers appear about equally white when one is in deep shadow and reflecting as little as 1/3000th the amount of light from the paper in bright illumination. Similarly chromatic objects "pick out" their dominant wave-length in strongly chromatic illuminations and thus appear

quite "normal" even though the light they send to the eye differs radically from normal. At first thought it might seem that this ability to separate the reflectance of the object from the quantity and quality of the illumination is due to learning, memory, judgment, or imagination. Experiments with young children, chimpanzees, rhesus monkeys, hens, and even fishes show that animals below adult man possess constant colors no less than he.

As a result of the work on constancy it is now known that colors possess more than the three classical dimensions of hue, brilliance, and saturation or purity. These dimensions fully characterize colors seen only in the aperture or film mode, that is in spectroscopes and behind small holes in gray screens. Colors seen as belonging to surfaces have in addition the dimensions of whiteness, insistence or liveliness, glossiness, and possibly others as well. Recent work has been directed toward obtaining quantitative measures of some of the new dimensions with promise of ultimate success.

According to Dr. Helson, the mechanisms responsible for constancy effects are not yet fully understood. It appears that the facts uncovered in connection with phenomena of constancy require reaximation and reformulation of mechanisms long thought to be well understood. The possibilities of explanation in terms of mechanisms having a physiological basis were discussed under the headings of adaptation, contrast, multiplicity of color dimensions, trigger mechanisms, and assimilative effects.

The investigations of constancy represent an enlargement of the sphere of scientific interest and include many observations of everyday life hitherto neglected but which now seem to be of the greatest practical and theoretical importance.

Informal Dinner

An informal dinner at the Hotel Pennsylvania was attended by about one hundred members of the Optical Society, the Inter-Society Color Council and their guests. Officers of the two organizations were introduced by President A. G. Worthing.

The dinner was followed by a lecture on Visual Processes and Color Photography by Ralph M. Evans of the Eastman Kodak Company, which was attended by a capacity audience of three hundred. Prefacing his paper, the speaker stated that the subject of color photography has developed through a combination of inventive genius and the direct application of chemistry and physics. Little attention has been paid to the subjective elements which enter in many ways into the problem. For the most part, this has been due to the fact that during the formation stages subjective problems could be controlled by simple inspection of the results and empirical modification of the technique. Color photography has now passed the formation stage, and although great advances are still to be made by direct experimental work, a need is arising for a well-founded theory, which will include all aspects of the subject.

Dr. Evans' paper was presented as a technical survey of the most important of the subjective phases of the subject, based in large part on three articles by the speaker, which are to be published in the near future. Its presentation as a lecture permitted the demonstration of effects which are difficult to describe adequately and, as far as possible, all the described phenomena were shown. The subject was discussed under three headings: approximate brightness constancy, chromaticity adaptation, and luminance in nature.

Under chromaticity adaptation were grouped approximate color constancy, simultaneous color contrast and successive color contrast as well as chromatic after-images, all of which were considered as phases of a single mode of action of the color receptors. The approach was qualitative rather than quantitative, and the ultimate consequences for color photography were considered.

Luminance adaptation occurs independently of adaptation to chromaticity. Three types of adaptation were described, based on the recent work of Wright and of Schouten. They were described as general, local, and lateral adaptation. All these can exist simultaneously in the retina. The first two are distinguished by long and brief periods of recovery due, respectively, to long or short exposures to the stimulus. The last is that caused by exposure of a neighboring area on the retina. Simultaneous and successive brightness contrast effects and the perception of

grays were treated as aspects of these types of adaptation.

The effects on the tone reproduction properties of a process as well as the importance of relative color brightnesses were considered briefly. Types of brightness "masking" now in use were described and the effects demonstrated.

Symposium on Color-Blindness and Color-Blindness Tests, Arranged by the Inter-Society Color Council

The second symposium, held on Saturday morning, March 6th, was opened with a paper on the facts of color-blindness, by Deane B. Judd, of the National Bureau of Standards, who pointed out that color-blindness is of various types, and there is greater or lesser adherence of groups of observers to these types. The most common are the two types of red-green blindness, protanopia and deuteranopia, and the corresponding types of anomalous vision, protanomaly and deuteranomaly. Although red-green blind observers should obviously be excluded from occupations requiring the ability to make red-green distinctions, there is doubt what to do with an observer proved to be anomalous because, in spite of the fact that many anomalous observers have virtually no ability to distinguish red from green, others do so nearly or quite as well as normal observers.

Color-blindness is usually congenital, but it may also be acquired as a result of injury or disease. Congenital red-green blindness and anomalous vision are much more prevalent among males than among females, being a characteristic of about four percent of males and about one-tenth this proportion in females. These anomalies are regarded as sex-linked characteristics. Total color-blindness, however, is thought to be a simple recessive characteristic.

Red-green blindness is designated as a reduction form of normal vision, because two lights of whatever spectral composition required to produce a match for the normal observer will be indistinguishable by a red-green blind observer. Red-green weakness, or anomalous vision, on the other hand, is called an alteration form of vision, because such matches by the normal are frequently quite unacceptable to the anomalous observer. In spite of this it is possible to predict the brightness judgments of the anomalous observer with good validity from the normal specifications of the colors being dealt with, the chromaticity alone being unpredictable. Methods of predicting precisely the appearance of colors to red-green blind observers were described with a view to their possible usefulness in the design and development of color-blindness tests.

The specific utilitarian nature of tests in general, as contrasted with methods of experiment, was emphasized by Forrest Lee Dimmick of Hobart College in his discussion of methodology of test preparation. The concealed figures in charts such as the Ishahara are tricks; this consideration does not detract from the ingenuity of their inventors, but their value is now doubted. Such tests draw a sharp line between two groups of individuals; the question is raised whether such a dichotomy is wanted, or is a test desired that will yield a distribution of the population.

The size of the test object is an important factor in any test; large areas improve visual perceptions, and this effect detracts from the value of many eyepiece instruments. In the development of the I.S.C.C. tests the importance of this factor was soon found. The effect of spatial arrangement—whether right-left or left-right, up-down or down-up—appeared to be individual and unpredictable. The absolute intensity should be considerably above the scotopic limen. Not only discrimination, but also a qualitative judgment of the direction of the difference, was found to be a requirement. It may be concluded that in the preparation of tests for color vision, methods and methodology are all important.

The evolution of Color Vision Tests was discussed by Elsie Murray of Cornell University. Historically, the tests now current have evolved under triple pressure from discovery of unusual cases; release of color theories and hypothetical categories of defect; and national emergencies that involve color vision, as railway disasters, and modern warfare. During the last seventy-five years, under pressure of rapid transit and modernized warfare problems, hundreds of tests have been evolved, yet the perfect all-purpose test is still undiscovered. Tests may be classed accord-

ing to stimulus media employed (reflected or transmitted light); mode of recording; scoring method (all-or-none or quantitative); mode of administering as to individual or group, as to photopic or scotopic, according as daylight or dark adaptation is the rule; mental operations required, whether simple or complex, or whether motor or verbal responses are stressed. Examples under these several headings were shown, and pitfalls indicated. Among the tests described were the Holmgren-wool type test; the Nagel Anomaloscope; the lantern type test of Donders, Edridge-Green, and derivatives; "vanishing pattern" tests; classification, serial arrangement, and matching tests.

An instrument for the study of the red-green and yellow equation was described by Selig Hecht of Columbia University. The ratio of red and green light in a mixture can be changed by the observer to match a yellow light of adjustable intensity; used as subjects were normal observers and also a large number of Army rejects. Contrary to Houston and others, there are three sharply divided categories. The method was described as both an experiment and a test which will at least pick out the normal observers, and makes a quantitative statement of the anomaly found.

D. L. MacAdam of the Eastman Kodak Company described and demonstrated several tests which have been devised for the measurement of degrees of anomaly in terms of standard colorimetric quantities. Wave-length discrimination at 560 millimicrons has been employed for the rapid detection and specification of degree of anomaly of color vision. The kind of anomaly cannot be classified by this test and its use can be justified for specific applications only by successful correlation with the performance of the visual tasks expected of observers selected on this basis. A practical form of this test employs a green (dominant wave-length 560 millimicrons, 97 percent purity) Landolt (C) ring on a yellow (dominant wave-length 584 millimicrons, 98 percent purity) ground having the same luminance as the Landolt ring. An image of this pattern is projected onto a somewhat larger uniform green field having the same dominant wave-length and purity as the Landolt ring. The dominant wave-length difference of the two parts of the observed pattern depends on the ratio of luminances of the image and of the uniform green field, and is adjustable by simple means. The break in the ring is exhibited automatically in an erratic sequence among eight equally spaced orientations and eight correct out of ten observations are used as the criterion of discrimination. Moderate intelligence and high motivation are necessary for the successful use of this test.

A method for classification of individuals in industry was described by Frederick W. Jobe of the Bausch & Lomb Optical Company. A portable instrument which can be transported to the worker in the factory has been designed; the test, which is limited to practical considerations is easy to administer, and is quite rapid. Correspondence between rating of color vision and general efficiency in certain activities has been observed. Modifications of the instrument for the examination of normal color vision were proposed.

The Farnsworth-Munsell 100-hue test for color vision was described by Dean Farnsworth of New York University as a laboratory device for examination of color vision. It employs a selection of the Munsell 100-hue circuit; the data obtained are interpreted by means of a uniform chromaticity scale diagram, the construction of which was described. Many applications of this test were discussed, including its use as a control on other tests; to detect and identify types of color anomalies; as a check on special remedial measures, such as monochromatic excitation and vitamin A dosage; and to furnish information for the construction of new tests. As a sample of the many tests which may be constructed, a dichotomous test for color vision was described which classified a population into normal and color-blind groups at a given point of deficiency necessary to a particular industry.

The Inter-Society Color Council Single Judgment Test for red-green discrimination, described by Dr. LeGrand H. Hardy of the Institute of Ophthalmology, arose from the development by the I.S.C.C. of a test for color aptitude.

From the Pitt data on iso-color zones for the protanope and deuteranope two series of colored chips were made: the first series (protanope) extending in 40 steps from Munsell N5/ to 6R 5.4/4; the second (deuteranope) series extending

from Munsell N5/ to RP 5.0/4. From these chips 20 pairs presenting 2, 3, 4, 5, and 6 j.n.d.'s were mounted on a 15-inch disk inside a casing. These 20 pairs presented first through an opening on the right, then through one on the left, yield a 40 single-judgment record. Specifications include standardized conditions of illumination, of viewing, of warming up, of administration, of recording and interpreting. The space-error is compensated. A rational scoring system yields quantitative results diagnostic of R-G blindness, R-G defective discrimination, protanomalous or deuteranomolous, R-G defective undetermined type and normal.

The test is self-contained, automatic in character and yields a punched-out record of performance, which eliminates the personality factor of the administrator and other environmental variables.

Contributed Papers

The abstracts of the contributed papers are appended.

Meeting of the Board of Directors

A meeting of the Board of Directors was held on Thursday, March 4. The minutes of this meeting are printed elsewhere in this issue.

Program of Sessions

(Titles and Abstracts of Papers)

Symposium of Invited Papers

VISION

1. **Factors in Human Visual Resolution.** Gordon L. Walls, *Bausch & Lomb Optical Company.*
2. **Some Aspects of the Eye as an Image-Forming Mechanism.** Kenneth N. Ogle, *Dartmouth Eye Institute.*
3. **Dark Adaption: Some Physical, Physiological, and Clinical Considerations.** Charles Sheard, *The Mayo Foundation.*
4. **Some Factors and Implications of Color Constancy.** Harry Helson, *Bryn Mawr College and The Foxboro Company.*

Contributed Papers

5. Conditions for High Contrast in the Twyman-Green Interferometer, Harold Osterberg, *Spencer Lens Company.*

The problem is to investigate the conditions under which best fringe contrast may be obtained in the Twyman-Green interferometer, whose mirror arrangement is similar to that of the Michelson interferometer. Considerable difficulty arises in recoating the dividing mirror so as to obtain good fringe contrast, especially when stray light cannot be eliminated. It will be shown that the reflecting power of the front surface of the dividing mirror should be rendered as low as possible, as for example by a non-reflecting film. If metal is used to coat the back or dividing surface, there exists an optimum value of the glass-metal reflecting power. This optimum value depends upon *both* the reflecting power of the front surface and the amount of stray light present. That the optimum reflecting power should depend upon the magnitude of the stray light was unsuspected. Fortunately, this provides a means for reducing the effects of stray light upon fringe contrast. The reflecting power of the end mirrors should be high. Unless the stray light is caused by scattering from the mirrors, etc., the incident light beam should be of high intensity. The theory is applied to the case of a dividing mirror (spectacle crown) whose front surface is coated with magnesium fluoride and whose dividing surface is aluminized. The dependence of fringe contrast upon the reflecting power of these surfaces is marked. The optimum value of the glass-aluminum reflecting power, R, falls in the range 35–45 percent. If the front surface of the dividing mirror is not coated with a low reflecting film of magnesium fluoride, the optimum value of R falls in the higher range 40–55 percent. The fringe contrast varies slowly for values of R which are near the optimum values but falls rapidly for other values of R. When the Twyman-Green interferometer was treated in accordance with the above principles, very marked improvements in fringe contrast were obtained. Experiment is in excellent qualitative agreement with the theory. It is sometimes helpful to polarize the incident light beam.

6. Final Report of the O.S.A. Subcommittee on the Spacing of the Munsell Colors. SIDNEY M. NEWHALL, DOROTHY NICKERSON, AND DEANE B. JUDD.

A reproportioned and greatly enlarged Munsell solid has been developed from extensive visual estimates by numerous observers of the *Munsell Book of Color* samples.[1,2] All three dimensions have been smoothed and respaced. The new adjusted lines of constant hue have been extended closer to the extremes of value while the loci of constant chroma have been extrapolated to the pigment maximum.[3] The dimension of value has been redefined without substantial departure from the Munsell-Sloan-Godlove figures.[4] The new solid has been standardized in terms of the I.C.I. standard coordinate system, Illuminant *C*. These changes result in a closer approach to A. H. Munsell's dual ideal of psychologically uniform spacing and practical usefulness. This paper is a summary of the more recent work of the Subcommittee of the Colorimetry Committee on the Spacing of the Munsell Colors.

[1] Munsell Color Company, *Munsell Book of Color*, Standard edition, 20 hues; Abridged edition, 20 hues (1929), Abridged edition, 40 hues (1942).
[2] S. M. Newhall, "Preliminary report of the O.S.A. subcommittee on the spacing of the Munsell colors," J. Opt. Soc. Am. **30**, 617 (1940).
[3] D. L. MacAdam, "Maximum visual efficiency of colored materials," J. Opt. Soc. Am. **25**, 361 (1935).
[4] A. E. O. Munsell, L. L. Sloan, and I. H. Godlove, "Neutral value scales. I. Munsell neutral value scale," J. Opt. Soc. Am. **23**, 394 (1933).

7. A Psychological Color Solid. DOROTHY NICKERSON, *Food Distribution Administration, U. S. Department of Agriculture,* AND SIDNEY M. NEWHALL, *Arlington, Virginia.*

In the preparation of a report on the smoothing of the Munsell colors,[1] data have become available that permit an approximate fulfillment of the four following requirements for an ideal psychological solid in cylindrical coordinates: (1) the dimensional scales to be calibrated to perceptually uniform steps, (2) the units of the several scales either to be equated or the relation among them known, (3) the surface of the solid to represent all colors of maximum strength and contain a volume representative of all colors which would be perceptible under the prescribed conditions of viewing, and (4) the scale to be standardized in terms of psychophysical equivalents. A color solid based on such data[1] will be presented.

[1] Sidney M. Newhall, Dorothy Nickerson, and Deane B. Judd, "Final Report of the O.S.A. Subcommittee on the Spacing of the Munsell Colors," this program, preceding abstract.

8. Inclusion of Visual Adaptation in a Metric for Color Space. DOMINA EBERLE SPENCER, *American University, Washington, D. C.*

In a previous paper[1] a Euclidian metric was developed on the basis of the MacAdam data[2] on color discrimination. All other previous papers that treated a metric for color space ignored the effect of visual adaptation; but in the previous paper[1] the metric was extended to include adaptation. This procedure results in a metric in terms of the composite color stimulus.[3] In the present paper, the previous work is extended to cover a much wider range of composite stimuli than that covered by the data on color discrimination. The metric coefficients for the wider range are based on the most recent data of the O.S.A. Subcommittee of the Spacing of the Munsell Colors,[4] and the result is again a Euclidian metric space. With the eye adapted to a neutral gray, this new space is found to give straight lines for constant hues of the Munsell system and to give uniformly spaced circles for constant chromas. This particularly simple representation should be of importance in the revision of the Munsell system and in the extrapolation of the Munsell notation to the theoretical limits.[5]

[1] D. E. Spencer, "A metric for color space," presented at O.S.A. meeting, October, 1942; J. Opt. Soc. Am. **32**, 744A (1942); P. Moon and D. E. Spencer, "A metric for color space," to be published.
[2] D. L. MacAdam, "Visual sensitivities to color differences in daylight," J. Opt. Soc. Am. **32**, 247 (1942).
[3] D. E. Spencer, "Adaptation in color space," J. Opt. Soc. Am. **33**, 10 (1943).
[4] "Final report of the O.S.A. subcommittee on the spacing of the Munsell colors," this program, Abstract No. 6.
[5] D. L. MacAdam, "Maximum visual efficiency of colored materials," J. Opt. Soc. Am. **25**, 361 (1935).

9. The Supplementary Selected Ordinate Method of Tristimulus Integration. GEORGE W. INGLE, *Monsanto Chemical Company, Plastics Division.*

For routine use in color problems involved in the production of plastic materials, accuracy, simplicity, and speed in tristimulus integration are important. Calculation with thirty—and even one-hundred—selected ordinates, particularly by an operator without specific training, produces variations in these factors with certain curve shapes. These differences may be prohibitively large. The use of 10-mμ interval weighted ordinates, with a provision similar to that devised by Razek[1] for increasing the speed and convenience, shows definite improvement over the selected-ordinate method for recorded spectrophotometric curves exhibiting extreme selectivity. Comparable accuracies obtain for the integration of less selective curves by these methods. Dr. MacAdam of the Eastman Kodak Company has developed the supplementary selected ordinate method of tristimulus integration, a description of which will be presented in a forthcoming report of the Colorimetry Committee of the Optical Society of America. This process improves the accuracy of the standard selected ordinate method by providing for the inclusion of properly weighted values of reflectance (or transmission) at supplementary wave-lengths in the ranges where the thirty standard selected ordinates are widely spaced, i.e., where the tristimulus functions exhibit minima. Glass templates have been prepared which incorporate these data supplied by Dr. MacAdam. In conjunction with printed forms this simple method has proved extremely accurate and convenient for use in integrating even the most selective curves.

[1] J. Razek, J. Opt. Soc. Am. **26**, 225–226 (1936).

10. Color Designations for Lights. KENNETH L. KELLY, *Research Associate at the, National Bureau of Standards, representing the American Pharmaceutical Association.*

Ever since the development of the ISCC–NBS (Inter-Society Color Council-National Bureau of Standards) system of color names for the description of the colors of drugs and medicines, a need has been recognized for a system of color names for the description of the colors of

lights. Somewhat conflicting color names are regularly used in the description of the colors of flares, landing lights, and some beacons and signal lights. A tentative extension of the ISCC–NBS system has been worked out for lights. The color names consist of high value hue names such as red, pink, orange, green or purple, but no low value hue names such as brown or olive. Modifiers are not used because the conditions of lighting and viewing are too variable and because the problem is usually one of separating lights of different hues. The hue names are those used in the ISCC–NBS system and carry the same meaning. The chromaticity ranges identified by each of these hue names are defined by areas on the ICI chromaticity diagram. The constant-hue boundaries center on the point representing standard Illuminant *C*, and extend out to the spectrum locus. The curvature of the constant-hue lines is derived from the Newhall smoothed Munsell data extended to the spectrum locus, the extensions being guided by the color judgment of a number of source-filter combinations whose chromaticities fall on or near these lines. Comparisons are made between the centers of the proposed hue-name ranges or true hues and similar values reported by a number of authorities. Comparisons are also made with the standard colors recognized in various formal specifications for marine, railway, aviation, and highway traffic signal glasses.

Symposium of Invited Papers

PART I. COLOR-BLINDNESS

11. Facts of Color-Blindness. DEANE B. JUDD, *National Bureau of Standards.*

12. Why Color Normals are Necessary to the Various Services. Representatives of the Armed Services.

13. Methodology of Test Preparation. FORREST LEE DIMMICK, *Hobart College.*

14. The Evolution of Color Vision Tests. ELSIE MURRAY, *Cornell University.*

Representatives of the Armed Services.

PART II. COLOR-BLINDNESS TESTS

15. The Red-Green and Yellow Equation for Normal and Color-Blind Observers. SELIG HECHT, SIMON SHLAER, AND JAMES C. PESKIN, *Columbia University.*

16. Hue Discrimination Test for Anomalous Color Vision. DAVID L. MACADAM, *Eastman Kodak Company.*

17. A Method of Testing Color Vision Using Colored Transparencies and Standard Conditions of Observation. FREDERICK W. JOBE, *Bausch & Lomb Optical Company.*

18. The Farnsworth-Munsell 100-Hue and Dichotomous Tests for Color Vision. DEAN FARNSWORTH, *New York University.*

19. The ISCC Single Judgment Test for Red-Green Discrimination. LEGRAND H. HARDY, *Institute of Ophthalmology.*

Contributed Papers

20. Description of a Subject Congenitally Deficient in Violet-Yellow Vision. DEAN FARNSWORTH, *New York University.*

Father and two sons exhibit the three known types of dichromatic vision—the father is violet-blind, one son is red-blind, and the other green-blind. The father, Mr. V., has a personal history of health, free from accidents, and exhibits no ocular abnormalities. Instances of specific confusions of violet with yellow, blue with green, and orange with red-purple have occurred since his twentieth year. Mr. V. gives normal responses on all pseudo-isochromatic plates, passes the ISCC Red-Green discrimination test and a replica of the Canadian Lantern. However, he tests violet-yellow anomalous on the Farnsworth Dichotomous Panels and the F–M 100-Hue Test, and matches, with slight adjustment in brightness, all Munsell colors on the same value level which parallel the purple-redpurple and yellow-greenyellow axis. The violet region of the spectrum is invisible to the subject and a neutral division occurs where normals describe yellow. Any part of the spectrum can be matched in hue with any other part on the same side of neutral. Detailed procedure and data will be presented. The type is entirely unlike the one presented by Robinson[1] and cannot be compared with Huntington's[2] because of Huntington's failure to present a spectral analysis. Several persons with the same anomaly have been detected by the 100-Hue Test and the Dichotomous Panels which indicates that the occurrence of violet-yellow dichromatism is not as uncommon as has been generally supposed, but has passed undetected because of the inadequacy of the testing procedure.

[1] F. Richardson-Robinson, "A case of color-blindness to yellow and to blue," Am. J. Psychol. **34**, 157–184 (1923).

[2] C. E. Huntington, "A case of apparent blue-blindness," Am. J. Psychol. **44**, 185–188 (1932).

21. Analytic Approximation of Standard Trichromatic Data. PARRY MOON, *Massachusetts Institute of Technology.*

A previous paper,[1] "Analytical Representation of Standard Response Curves," treated various equations for representing standard spectral-response data and showed that the Pearson Type V equation[2] has many advantages for this purpose. The present investigation applies this formula to the analytic representation of the C.I.E. trichromatic data. These data have been given previously in the form of tables, and thus mathematical manipulation has been possible only by cumbersome numerical computation. The introduction of analytic representations of $\bar{x}$, $\bar{y}$, and $\bar{z}$ simplifies theoretical work on color. As with any reasonably simple mathematical representation, the proposed equations do not fit the C.I.E. data exactly. It is shown, however, that the differences between the new values and the standard ones are generally less than the experimental variation between observers; so the new results may well be as good an approximation to average color vision as the C.I.E. values. One of the principal advantages of analytic representation is that in many cases it allows simple analytic integration and differentiation. Formulas are given for obtaining X, Y, Z, x, and y for Planckian radiation and for any arbitrary radiation that can be represented by a power function of wave-length. These integrated values are ordinarily within a few tenths of one percent of the values obtained by the former methods of numerical quadrature. Tables and graphs are given which show the accuracy of the new method.

[1] P. Moon and D. E. Spencer, "Analytical representation of standard response curves," J. Opt. Soc. Am. **33**, 89 (1943).
[2] K. Pearson, "Supplement to a memoir on skew variation," Phil. Trans. Roy. Soc. **197A**, 446 (1901).

22. Standard Response Functions for Protanopic and Deuteranopic Vision. DEANE B. JUDD, *National Bureau of Standards.*

Protanopic and deuteranopic vision, the two forms of red-green blindness fairly common among human males, are known as reduction forms of normal vision; that is, two lights of whatever spectral composition is required to appear alike to a normal observer will also be indistinguishable to a protanope or a deuteranope. It is therefore possible to find a pair of linear homogeneous transformations of the functions representing normal vision to represent in turn each type of red-green blindness as is exemplified by the König *Grundempfindungskurven.*[1] As a result of a search for the simplest possible representation, it has been found that deuteranopic vision can be represented closely by two functions, K and W_d, and protanopic vision by two functions, K and W_p, defined in terms of the 1931 ICI standard observer[2] simply as:

$$K = Z,$$
$$W_d = Y,$$
$$W_p = -0.4603X + 1.3590Y + 0.1013Z.$$

The luminosity function of the deuteranope is substantially the same as that of the normal observer and is therefore represented by $W_d = Y$. The luminosity function of the protanope is represented by W_p. If the functions K, W_d, and W_p be taken together they represent normal vision. The chromaticity confusions of a protanope may be evaluated colorimetrically in terms of this normal system as shown by Maxwell[3] by drawing on the Maxwell triangle straight lines through the point representing the primary whose function is W_d. Similarly the chromaticity confusions of a deuteranope may be shown by lines through the W_p primary. The degree to which these chromaticity confusions correspond to those found experimentally by Pitt[4] will be demonstrated. These functions serve the useful purpose of making conveniently accessible by computation the average color confusions of the deuteranope and the protanope, and they suggest a variation of the Young-Helmholtz theory of vision which may also be worthy of consideration because of its simple explanation of total color-blindness. This variation does not, however, account in any simple way for the facts of chromatic adaptation as does Wright's variation;[5] nor does it account for the sensations of the various types of vision as does the Müller theory.[6]

[1] A. König, *Gesammelte Abhandlungen* (Barth, Leipsig, 1903), p. 214.
[2] D. B. Judd, J. Opt. Soc. Am. **23**, 359 (1933).
[3] J. C. Maxwell, *Supplement to Researches on Colour-Blindness* by G. Wilson (Sutherland-Knox, Edinburgh, 1855).
[4] F. H. G. Pitt, Characteristics of Dichromatic Vision, Med. Res. Council, Sp. Rep. Ser. No. 200 (London, 1935).
[5] W. D. Wright, Proc. Roy. Soc. **B115**, 49 (1934).
[6] G. E. Müller, Über die Farbenempfindungen, Zeits. f. Psychol. Ergänzungsb. **17** and **18** (1930).

23. Conditions for Dyestuffs Spectrophotometry and Some Techniques. I. H. GODLOVE, *E. I. du Pont de Nemours & Co., Inc.*

This subject will be discussed and developed by showing that the relations of dyestuff control and spectrophotometry may be considered as of a dual nature. The very complications which, on the one hand, are serious difficulties, on the other hand suggest or adapt themselves to the development of techniques for solving many of the problems of the industry. A picture of the conditions for dyestuffs spectrophotometry will be drawn. Some subjects which will be touched upon are impurities in commercial dyes and the reasons for their inevitable presence; variability of color with substrate; need for special solvents; mass-action effects of water; cases where colors of the dyes measured bear no relation to the colors as used in practice; Beer's law failure; tautomerism and polymerization; flocculation; aftertreatments; instability on storage; deliquescence, turbidity, and colloidal phenomena; adsorption and chromatography; selective solubility; particle size; "exhaust" variability; addition of "shading" dyes in standardization; spectral match *versus* colorimetric match; and time saving.

24. Analysis of Some of the Chemists' Concepts of Color. I. H. GODLOVE, *E. I. du Pont de Nemours & Co., Inc.*

This paper briefly reviews the evolution of the chemists' concepts of light absorption and consequent development of color. A recent view of the chemists is pictured as a strife for possession of electrons which propagandists might liken to the warfare between the forces of "have" and

"have not" atoms. Oxidized chromophores of the old theory are the aggressive "have nots"; reduced auxochromes try to hold on to their electrons. Salt formation is a mechanizing of the forces, intensifying the warfare. A part of the struggle (color) is a "fifth-column" activity, infiltration of forces into the field of the neighboring atom which loosens the loyalty of the electrons for their home atoms. The result is a decrease of "isolationism," electrons executing longer and longer vibrations resulting in "deeper" and more intense absorption. The importance of mobility of the forces (absorption and transfer of energy), in the stabilization and breaking of lines, is pointed out. Computations are made of the series of colors, which the chemist describes as of increasing "depth," obtained when an absorption band moves across the spectrum. MacAdams' concept of the "maximum visual efficiency" of colored materials is used to examine some of the chemists' and dyers' concepts.

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Book Reviews

Sensation and Perception in the History of Experimental Psychology. E. G. BORING. Pp. xv+644. New York and London, D. Appleton-Century, 1942.

This volume supplements an earlier work by Professor Boring—*A History of Experimental Psychology* (1929)—which gave essentially a biographical account of the men who shared in bringing experimental psychology into being. The present work surveys the data that have accumulated in the experimental psychology of sensation and perception.

The new work contains sixteen chapters. The first two are introductory, although written last. Then follow six chapters on visual topics, three on auditory, and one each on—smell and taste, tactual sensibility, organic sensibility, and perception of time and movement. There is a final prospect as regards scientific progress.

The opening chapter emphasizes the cardinal position that perception has always occupied both in experimental and in systematic psychology. Here are recorded how the terms sensation and perception came to be distinguished, various changes in the usage of these concepts, and how their meanings are altered to suit current psychological systems. This chapter also includes a discussion of some of the experimental methods which have been utilized in these fields.

The second chapter traces trends which emerge as views regarding the physiological conditions now assumed to be the basis of sensation. Views that have been and are now held regarding nervous transmission are summarized, and the concepts of sensory projection and psychoneural isomorphism are considered. However, the reviewer is surprised to find that these theoretical considerations have not been adapted so as to engage with the reality of a substantial body of information on potential changes that are known to be induced in the cerebral cortex during sensory stimulation; particularly, in view of the fact that in another context the significance of potential changes which are associated with activity in the eighth cranial nerve is discussed and illustrated in some detail.

In the subsequent chapters, which comprise the main part of the work, Dr. Boring seems to undertake essentially a twofold task: (1) to provide an historical survey of the experimental data that have accumulated in various sensory and perceptual fields, and (2) to review the theoretical views that have been advanced to explain the known phenomena in various sensory fields.

As regards the first task, the author has reviewed a large body of experimental literature on each of the senses and on perceptual topics as well. The ways in which the experimental method has been adapted to the needs of a great diversity of sensory and perceptual problems are revealed, and the manner in which psychophysical measurement is employed in the investigation of the related neurophysiology is indicated. The survey is extensive in scope, and of course sacrifices had to be made to bring the work within the limits of a single volume. The data on flicker are missing, and some of those on stimulation-deafness get into the notes if not into the text. The problem of reading is not included. The history of the various acuities belongs here, but experiments on tactual acuity are the only ones specifically treated. The exposition regarding many important studies seems too condensed. Olfactory and gustatory adaptation are compressed to a single paragraph each, and Hahn's important study is not mentioned. The extensive literature on muscular sensitivity is certainly over-condensed. There is a trend of historical evidence which could have been used as the basis for bringing the general problem of sensitivity in the various senses (so important to-day) into sharper focus.

The treatment regarding theory is different for the various senses. A separate chapter is allocated to this matter for vision and for audition. Although various visual theories are described, and a number of modifications are mentioned, the theories of Adams, Schanz, and Schjelderup are among those not included. Auditory theory is discussed in terms of electrically recorded potential changes which are known to attend activity in the auditory system, but "modern visual theory" is not related to the abundance of information regarding potential changes that has been secured from various parts of the visual apparatus by Bartley, Graham, Granit, Hartline, and many others. Partly for this reason the treatment concerning auditory theory is more thoroughgoing.

For the other senses, theory is interfused with the historical account of experimental data. Olfactory theory is dismissed with the statement that there never has been a thoroughgoing chemical theory. Gustatory theory might have been strengthened by reference to the views of Lasareff, Renqvist, and Taylor. As regards tactual sensibility, the views of von Frey and Head are contrasted, but Nafe's arguments against the conventional "spot" theory have merited no more than a mere indirect reference. In the discussions concerning smell, taste, touch, and kinesthesis the theoretical consideration is restrictive, being concerned too exclusively with specifying the number of receptors that are required and what they are believed to be. Here at least the principles of projection and isomorphism might have been employed the more adequately to indicate the nature of dynamical changes that occur in a population of coacting neuro-receptor cells when diverse sensory and perceptual phenomena are eventuated.

Despite these details regarding its shortcomings, the volume is clearly written and well annotated, and it is bound to serve an important function. In developing the idea that thought is continuous, it shows that a sound historical perspective is indispensable both to a proper evaluation as regards present status and to an adequate prospect as regards problems that are still pressing for solution. Its appearance is timely, too, when present-day considerations are rapidly dispelling all doubts as to the real and practical importance of sensory and perceptual problems among investigators in all branches of science.

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The Vertebrate Eye and its Adaptive Radiation. GORDON LYNN WALLS. Pp. 785+xiv. Published by Cranbrook Institute of Science, Bloomfield Hills, Michigan, 1942.

The essential function of vision is to explore the environment by the use of light. This is accomplished in the vertebrate eye by an optical system whose main elements are cornea, iris, lens, and retina. In the evolution of organisms, structure and function are reciprocally determined, and they are inextricably woven in the tissues of life. Therefore, the almost endless variety which the eye shows in its detailed structure must be an expression of its diversity in function. It is this comparative biology of vertebrate vision which is the subject of the present book, and it has been written by one who is enchanted by his subject and who speaks out of the fullness of his knowledge.

The volume is in three sections called basic, ecologic, and synoptic, respectively. The first section occupies 139 pages and deals almost exclusively with the human eye. Its purpose is to introduce the novice to terminology and general ideas, and to the specific structures and functions of the eye. There are chapters on the perception of light, on the structure of the eye, on the retina, on the visual process, on the genesis of the eye, and a final short one on the family connections of vertebrates, the latter for the orientation of the non-zoological reader.

The second or ecologic section runs to over 400 pages and is concerned with the adaptations to various external conditions which the eye has undergone in its evolution. One chapter tells about retinal photomechanical changes and pupil mobility; another about the structures and changes relating to day vision; still another about night vision. One chapter deals with adaptation to media and substrates, and includes data on aquatic vision, aerial vision, and air-and-water vision; still another chapter discusses adaptations to spectral differences, and presents the problems of color vision.

The third or synoptic section occupies 134 pages. Here in systematic fashion are described the detailed structures of the eyes of animals from fish to man. The emphasis is not only on the way the eye is built, but on its evolution, and on the evidence which the eye can give about the course of evolution.

All three sections are profusely illustrated with hundreds of drawings and diagrams. They are meticulously done with fine artistry, and add greatly to the book's value and attractiveness. There is a moderate bibliography—of which more in a moment—and an elaborate and excellent index.

The book as a whole is well written, in a style whose professional crispness is periodically punctured by a colloquial freshness which gives it bounce and personal flavor. Most of the significant biological problems of vision have been faced fairly and given original treatment. The result is a generally readable and at times fascinating book. Indeed, it is so good a book that one is disappointed by its failure to be better.

The reasons for this disappointment are inherent in the structure and plan of the book. It is evident, even from the summary just given, that the author has attempted three tasks: first, a brief elementary introduction to vision; second, an extended study of the structures of the eye in their relation to the animal's special habits; and third, a systematic catalog of the finer morphology of the eyes of vertebrates. These are three separate problems which require different treatments and different styles, and could well have been published as separate volumes. The author has complicated his task even more by attempting something which "will be of particular benefit to zoologists and ecologists, medical and veterinary ophthalmologists, and comparative psychologists," and which will "be entirely clear to any college student or graduate, and to any amateur naturalist—'trained' or not." The result of such an ambitious and inclusive undertaking is bound to be a compromise which can suit nobody consistently.

This lack in unified treatment shows itself in the separate sections. The first part is unevenly didactic; in one place there is a most elementary explanation of refraction by analogy with soldiers passing through a wheat field, while in another there is a long presentation of some unconfirmed and probably incorrect work on the photosensitive substance of the cones, which could have been dismissed in a sentence. To achieve simplicity and continuity, statements are made *ex cathedra* without evidence and generally without mention of specific authors. Since the reader has no

recourse to the original information, he cannot differentiate the controversial from the established, nor the error of judgment from the error of fact. The author's decision must be accepted as final, which means that in addition to a lot of sound critical sense, this part enshrines some errors and prejudices.

Because the real heart of the book is in its second section, this is better written, more balanced, more detailed, and more documented than the first part. Much of it records the author's own work; and when not, it presents his critical evaluation of the work of others. Walls is at his best here. His erudition, his phenomenal knowledge, and his hard sense make this an organization and synthesis of a whole range of phenomena never before treated as a unit. The sixty pages on the color vision of animals alone form an admirable critical summary to which many of us will frequently return, fully appreciative of its excellence.

The third section is the least interesting. It describes a series of structures one after another, and lacks the living touch that goes with function.

The most disappointing aspect of this volume again comes from the confusion of its professed purpose. In the preface the author says that the book is not designed as a reference work. Instead he hopes—"naïvely of course"—that it will be read through continuously, as a textbook. I am afraid that only a rare and extraordinarily impassioned student will read 688 pages packed with new stuff in this way. Indeed, it is hard to understand the presence of a carefully compiled index occupying 64 pages of fine print in terms other than the design of a reference book. More is the pity, therefore, that the text is not specifically documented, and that its bibliography is limited. One will frequently turn to this book to read a chapter, or to look up a particular structure, or to discover the habits of an animal with a special eye, and one will be sure to get fascinating information. But to find where this information comes from and to get more of it, the reader will have to look through several papers to locate the right reference; otherwise he will have to write to the author, as suggested, to learn the original source. Luckily the author is alive and vigorous, and a provocative correspondent, as I can testify; but it still would be better to have a reference in the text and a title in the bibliography. Scholarship has its responsibilities; and if they had been met, the result would have been not merely an informative and interesting book, but a fine and useful one as well.

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